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ELECTROPHYSIOLOGICAL PATTERNS OF SENTENCE SUPERIORITY EFFECT IN SENTENCE REPETITION

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ABSTRACT

Purpose: The current study aimed to investigate the behavioral and electrophysiological patterns of the sentence superiority effect (SSE) in sentence repetition in monolingual adults with typical language development. The ultimate goal of this study is to establish the foundation for future studies of SSE in sentence repetition in individuals with DLD.

Method: Twenty-three English-speaking monolingual adults completed a word list recall task (WLR). SSE with and without background noise was measured using WLR. Neural oscillations in the beta (13 – 30 Hz) and delta (1 – 4 Hz) frequency bands were analyzed. Sentence repetition, digit span forward and backward, LexTALE, and picture naming were conducted to examine the association between the neural oscillations in WLR and the cognitive-linguistic measures.

Results: SSE was observed in both behavioral accuracy and the beta and delta-band neural oscillations. Behavioral accuracy was higher in sentences compared to word lists. The beta and delta-band oscillatory powers were greater in sentences than in word lists, particularly in the last two words of the eight-word presentation. Both sentences and word lists in the beta and delta bands showed decreased power changes compared to the baseline. The effect of noise was found in behavioral accuracy, with higher accuracy in the condition without noise than with noise. No interaction between SSE and noise was found in either the behavioral or electrophysiological results. The delta-band oscillations showed a significant association with sentence repetition.

Conclusions: SSE in monolingual adults with typical language development is relevant to the beta and delta-band neural oscillations, particularly when the number of words exceeds the short-term memory limit of 4 ± 1 chunks. Behavioral and neurophysiological evidence demonstrates that SSE substantially enhances short-term memory capacity through the use of sentence structures. Further studies involving individuals with DLD are needed to verify the role of SSE in assessing individuals with DLD.

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Chapter 1

Introduction

Sentence repetition

Sentence repetition, also known as sentence recall or sentence imitation, is a task that requires listening to, remembering, and repeating sentences. The task is useful for assessing individuals with developmental language disorders (DLD), yet its underlying mechanism is unclear. The present study assumes that morphosyntactic processing is one of the factors that determine sentence repetition performance in individuals with DLD.

This study specifically focuses on the sentence superiority effect (SSE) as a potential factor influencing sentence repetition performance in individuals with DLD. I hypothesized that individuals with DLD may show a reduced sentence superiority effect in sentence repetition compared to individuals with typical language development due to their limited on-line morphosyntactic processing. I also expected that individuals with DLD may experience greater difficulties in morphosyntactic processing when background noise disturbs bottom-up processing.

However, no previous studies have examined SSE with and without noise in sentence repetition of individuals with typical language development. In order to understand SSE in typical language profiles, the current study targeted monolingual adults with typical language development. This study aimed to establish the foundation for future studies of SSE in sentence repetition of individuals with DLD.

Sentence repetition as a tool for assessing DLD

Children with developmental language disorders (DLD) are known to show deficits in recalling sentences compared to their peers with typical language development (TD). Since the relative difficulties in sentence repetition of children with DLD compared to TD are significant and consistent (Archibald & Joanisse, 2009; Redmond et al., 2019), the task has been used as a tool for measuring linguistic deficits in DLD either by itself or as a subset of a language assessment battery. For example, the Clinical Evaluation of Language Fundamentals-5 (CELF-5; Wiig et al., 2013) and the Test of Language Development-Primary: 4 (TOLD-P: 4; Hammill & Newcomer, 2008) are widely-used standardized language assessments that include sentence repetition as one of their subtests.

The effectiveness of sentence repetition in assessing language skills and deficits was first shown in first and second language acquisition studies (Flynn, 1986; Vinther, 2002). Sentence repetition was introduced in the field of language acquisition and disorders in the 1960s (Fraser et al., 1963; Menyuk, 1964) and in second language acquisition research in the 1970s, with the term *elicited imitation* (Naiman, 1974). After its advent, this task paradigm soon became a popular method in language research due to its simplicity in administration and flexibility in stimulus manipulation (Jessop et al., 2007). In addition to its convenience, many studies on sentence repetition have confirmed its effectiveness as a language measurement tool; it has high validity (Rondal et al., 1981), test-retest reliability (Gallimore & Tharp, 1981), correlation with other language skills (Zebib et al., 2020), and sensitivity and specificity in assessing language disorders (Archibald & Joanisse, 2009; Conti-Ramsden et al., 2001; Redmond et al., 2019; Stokes et al., 2006).

The effectiveness of sentence repetition in assessing individuals with DLD is evident in a variety of languages. Sentence repetition in different languages, such as Arabic (Taha et al., 2021), Cantonese (Stokes et al., 2006), Catalan (Gavarró, 2017), English (Riches, 2012), French (Leclercq et al., 2014), Mandarin (Wang et al., 2022), and Vietnamese (Pham & Ebert, 2020), has been shown to be effective in assessing individuals with DLD. Due to its efficacy in many languages, sentence repetition is regarded as a reliable instrument for evaluating linguistic difficulties in multilingual children with DLD. One such approach is the LITMUS Sentence Repetition Task (LITMUS-SRT; COST Action IS0804), which has its current version in approximately 28 languages when I searched in January 2023 (Marinis & Armon-Lotem, 2015). Marinis and Armon-Lotem (2015) provided the construction of sentence repetition tasks for multilingual populations with and without language impairments based on a set of principles in order to yield consistent results across languages. The LITMUS-SRT has been successful in the examination of DLD in culturally and linguistically diverse contexts (Marinis & Armon-Lotem, 2015).

Based on the effectiveness of sentence repetition in the assessment of individuals with DLD in many different languages, there is no doubt that sentence repetition is a useful and robust tool for the identification of DLD. Despite its broad use, the mechanism that enables sentence repetition to be an effective tool for examining linguistic difficulties in DLD has not yet been validated. This is due to the fact that sentence repetition performance is not driven by a single factor but can be affected by numerous components (Riches, 2012). Recent research has reached a consensus that sentence repetition is a multifaceted task that taps the functions and deficits of multiple linguistic and cognitive domains, including morphosyntax (Archibald & Joanisse, 2009; Seeff-Gabriel et al., 2010; Theodorou et al., 2017), semantics (Potter & Lombardi, 1990), phonology (Coady et al., 2010), and working memory (Aguilar-Mediavilla et al., 2019; Willis & Gathercole, 2001). Nonetheless, it is yet unclear how these components of sentence repetition interact with the cognitive-linguistic profiles of DLD and make the task a successful tool for the assessment of DLD (Klem et al., 2015; Polišenská et al., 2015; Riches, 2012).

Morphosyntactic difficulties in sentence repetition

As one of the factors influencing sentence repetition performance in individuals with DLD, many previous studies have highlighted morphosyntactic difficulties in sentence repetition (Archibald & Joanisse, 2009; Seeff-Gabriel et al., 2010; Theodorou et al., 2017). This is because morphosyntactic difficulties in sentence repetition of individuals with DLD are not only quantitively identified but also qualitatively distinctive compared to TD. Specifically, individuals with DLD tend to show more errors in syntactically complex sentences relative to simple sentences (Riches et al., 2010). Individuals with DLD are also more likely to produce sentences that are syntactically distant from target sentences than TD (Riches, 2012; Riches et al., 2010). Moreover, many morphosyntactic error types of sentence repetition in individuals with DLD are distinctive from the errors in TD (Frizelle & Fletcher, 2014; Meir et al., 2016; Taha et al., 2021).

Numerous studies have found distinctive morphosyntactic errors in sentence repetition in individuals with DLD compared to individuals with TD. Overall, individuals with DLD are more likely to produce errors that alter the target morphosyntactic structures than the errors produced by individuals with TD. For instance, Taha et al. (2021) found that both Palestinian Arabic-speaking children with DLD and TD showed the omission of grammatical morphemes and function words. However, only children with DLD produced fragmented structures due to the omission of several elements of the target sentence (Taha et al., 2021). Also, Meir et al. (2016) found that Russian-Hebrew bilingual children with DLD produced more omission errors that disturb the overall syntactic structures of a sentence (e.g., omission of coordinators, subordinators, and prepositions) compared to their bilingual peers with TD. Children with DLD in this study also showed frequent simplification of complex syntactic structures (e.g., changing object questions into subject questions, changing object relative clauses into subject clauses). These types of errors were not likely to be found in children with TD, whose errors were mainly driven by the L1 (Russian)-L2 (Hebrew) difference (Meir et al., 2016). Frizelle and Fletcher (2014) also found that children with DLD showed more morphosyntactic errors, including the simplification of complex sentences, the omission of obligatory relativizers, and the alteration of word order in the relative clauses than children with TD.

As described above, many previous studies confirmed that children with DLD demonstrate morphosyntactic difficulties in sentence repetition in contrast to those with TD. However, it is still unclear whether these morphosyntactic difficulties found in sentence repetition of individuals with DLD are primarily due to the lack of morphosyntactic knowledge or inefficient morphosyntactic processing. If the former is true, the majority of their morphosyntactic difficulties in sentence repetition should be resolved after they acquire sufficient morphosyntactic knowledge, at or after adolescence. Nonetheless, previous studies have revealed that the relative difficulties of individuals with DLD in sentence repetition compared to TD may persist through adolescence (Riches et al., 2010) and even adulthood (Poll et al., 2010). Therefore, it is plausible that the difficulties in sentence repetition in individuals with DLD cannot be solely explained by their lack of morphosyntactic knowledge but that the inefficiency of morphosyntactic processing also contributes significantly to their performance.

Also, studies that have investigated the difficulties with the processing of complex morphosyntactic structures in children with DLD imply that the difficulties in sentence repetition can be greatly affected by morphosyntactic processing deficits. For example, Hestvik et al. (2010) examined the off-line comprehension of sentences with relative clauses involving filler-gap dependencies, as well as the automatic on-line gap-filling test using the same sentences. The study revealed that children with DLD showed qualitatively similar results compared to TD children in their off-line comprehension but showed relative difficulties in automatic gap-filling after the relative clause verb (Hestvik et al., 2010). In addition, Marinis and Van der Lely (2007) suggested that children with DLD showed impaired on-line processing of wh-questions compared to TD children. While this study specifically focused on a subgroup of DLD (Grammatical-specific language impairment; G-SLI; Marinis & van der Lely, 2007) that demonstrates primary deficits in grammar, the finding shed light on the difficulties in on-line morphosyntactic processing in children with DLD, which can potentially explain the difficulties in their sentence repetition.

If morphosyntactic difficulties in sentence repetition of individuals with DLD are not solely explained by the lack of morphosyntactic knowledge but also can be influenced by processing inefficiency in morphosyntax, the inefficiency should be observed to understand sentence repetition difficulties in individuals with DLD. However, it is difficult to differentiate the effect of morphosyntactic knowledge and processing based on the accuracy of sentence repetition alone. If the sentence repetition task involves sentences with complex morphosyntactic structures, it will disclose more about individual differences in morphosyntactic understanding than the pure processing aspect. Conversely, if the sentence repetition task includes simple sentence structures only, there will be no behavioral accuracy difference between individuals with DLD and TD due to a compensatory mechanism for language processing in individuals with DLD.

Previous research has investigated the compensatory mechanism in sentence repetition utilized by individuals who recovered from DLD (Haebig et al., 2017). Haebig et al. (2017) found that adolescents who recovered from DLD showed a behavioral accuracy in the sentence processing task that was similar to their peers with TD, but the correlation patterns related to their event-related potentials were similar to the peers with persistent DLD, showing a significant correlation between the accuracy scores for the commission violation condition and mean amplitude differences in the N400 window. Also, both adolescents recovered from DLD, and the DLD-persistent peers showed relatively weak P600 compared to their peers with TD. The authors interpreted the results as compensatory semantic processing that substitutes for weak syntactic processing in adolescents recovered from DLD, which is not revealed by their behavioral results but found in their brain activities.

Haebig et al. (2017) denoted an important finding that electrophysiological methods like EEG may reveal processing difficulties that are not captured at the behavioral level. This finding also implies that a sentence repetition task in which electrophysiological activity differs but does not show a significant behavioral difference may reveal morphosyntactic processing that is unaffected or less affected by morphosyntactic knowledge in individuals with DLD. The significance of EEG in detecting subtle and internalized difficulties that are not detected at the behavioral level motivated the use of EEG, particularly neural oscillations, in the current study.

Working memory difficulties in sentence repetition

Although sentence repetition is well known as a language measure rather than a working memory assessment tool (Klem et al., 2015), there are some studies that highlighted the close relationship between sentence repetition performance and cognitive resources such as short-term or working memory in individuals with DLD. This is because sentence repetition involves the memorization of both the form and the meaning of sentences (Marinis & Armon-Lotem, 2015; Schweppe et al., 2015). Memorizing the form and the meaning of sentences requires minimal cognitive effort and resources if sentence processing is automatized (Jefferies et al., 2004). However, sentence repetition can be significantly affected by cognitive resources if sentence processing is not fully automated (Schweppe et al., 2015).

There are two key factors that contribute to the diminished degree of automated sentence processing and, consequently, the increasing demand for cognitive resources in sentence repetition. First, there are task factors. For example, if the length and complexity of the sentence stimuli exceed the typical working memory capacity, processing sentences would not be automatic and hence cognitively demanding. Second, there are intrapersonal factors. If a person's linguistic knowledge is immature (e.g., young children), not proficient (e.g., second language learners), or if a person has language disorders (e.g., individuals with DLD), their language processing is not fully automated; therefore, they may rely more on cognitive resources in sentence repetition than individuals with proficient and intact linguistic processing.

Among the cognitive resources, many studies shed light on the role of working memory in sentence repetition of individuals with DLD (Delage et al., 2021; Delage & Frauenfelder, 2020; Ebert, 2014; Poll et al., 2016; Pratt et al., 2021; Zebib et al., 2020). Working memory was a strong predictor of sentence repetition in bilingual children with DLD (Ebert, 2014; Pratt et al., 2021; Zebib et al., 2020) but not in bilingual children with TD (Pratt et al., 2021; Zebib et al., 2020). Working memory was also strongly associated with sentence repetition in monolingual children with DLD (Delage et al., 2021; Delage & Frauenfelder, 2020). Delage and colleagues found the association not only in children with DLD but also in children with TD (Delage et al., 2021; Delage & Frauenfelder, 2020). However, the results could be due to their use of complex syntax in sentence repetition, which already imposes cognitive demands in addition to the group difference. Also, Riches (2012) found that children with DLD may rely more on phonological short-term memory in sentence repetition than TD because their sentence repetition error rates were significantly correlated with nonword repetition scores, whereas the association was not significant in TD.

The role of working memory in sentence repetition of individuals with DLD motivated the present study to shed light on SSE, which will be discussed in the following section. SSE significantly reduces working memory demands by chunking via top-down processing, driven by the long-term morphosyntactic knowledge of individuals. Since SSE is known to alleviate working memory loads in sentence processing, the close relationship between working memory and sentence repetition in individuals with DLD should be reconsidered by incorporating SSE.

Sentence superiority effect

Why is SSE critical in sentence repetition?

Sentence repetition is less cognitively demanding when the processing of the sentences in the task is automated (Jefferies et al., 2004). Many studies have focused on the mitigated loads of working memory in sentence repetition compared to other types of verbal immediate recall and called the effect the *sentence superiority effect* (SSE): the benefit of utilizing the knowledge in sentence structures in recognizing, comprehending, and remembering sentences (Baddeley et al., 2009; Brener, 1940; Jefferies et al., 2004; Snell & Grainger, 2017). SSE is usually described as a relative benefit of processing sentences compared to scrambled words during encoding, storage, and retrieval of words (Allen et al., 2018; Baddeley et al., 2009). Baddeley (2012) mentioned that the memory span of scrambled words is around five, but the span can increase to fifteen if the words are in a sentence. SSE highlights how long-term linguistic information contributes to the on-line processing of working memory.

The long-term linguistic information generating SSE includes sentence-level morphosyntax and semantics because those factors are uniquely found in sentences compared to a random set of words. Specifically, the dramatic increase in memory span for words in sentences is known to be a consequence of chunking using top-down processing of morphosyntactic knowledge and sentence-level semantic information (Massol et al., 2021).

While many studies focused on the morphosyntactic interpretation of SSE, a question was posed whether SSE is solely a morphosyntactic effect minimally influenced by sentence-level semantics or a sentence-level effect encompassing morphosyntax and semantics in general. Recent studies found that sentence-level semantics plays an important role in SSE but with less influence compared to SSE interpreted by sentence-level morphosyntax. For example, Massol et al. (2021) found an interaction between syntactic and semantic effects in SSE, showing a greater SSE in semantically regular sentences relative to semantically anomalous sentences.

Moreover, even when using the same set of lexical items for sentences and word lists, it is difficult to completely control the influence of sentence-level semantics in SSE. This is due to the fact that the same words are more likely to be semantically recognizable in a sentence than in a scrambled sequence. Also, Polišenská et al. (2014) discovered that delayed sentence repetition indicates a semantic effect, while immediate sentence repetition reveals a morphosyntactic effect. Therefore, the current study using immediate recall is based on the hypothesis that SSE is mainly driven by morphosyntactic information but with the support of sentence-level semantic information.

SSE posits the top-down intervention of long-term linguistic knowledge, especially morphosyntactic knowledge, and processing in working memory. The top-down processing is not only helpful in improving verbal working memory capacity but also makes working memory resilient when coping with disturbances. For example, the increased accuracy in word processing facilitated by SSE was not dependent on the position of words in a sentence (Snell & Grainger, 2017). Also, SSE was maintained when using nonsense sentences (Baddeley et al., 2009), when using sentence fragments that are not complete sentences (Bonhage et al., 2014, 2017; Perham et al., 2009), when involving a secondary task that requires attentional allocation (Jefferies et al., 2004), and even when the words in sentences are backward (Roverud et al., 2020).

Background noise

The role of background noise in examining SSE

Compared to the numerous studies on the impact of background noise on the perception of sentences, there have been fewer investigations on the effect of background noise on sentence repetition (Drager et al., 2006; Hannigan et al., 1980). Nonetheless, previous studies have examined the relationship between background noise and linguistic characteristics that may influence sentence repetition. Several researchers, for instance, have examined the relationship between background noise and linguistic knowledge, such as phonological (Aly & Kanj, 2014), semantic (Hannigan et al., 1980), syntactic (Carroll & Ruigendijk, 2013), and general language proficiency (Krizman et al., 2017; Rogers et al., 2006; Scharenborg & van Os, 2019). These investigations discovered evidence that the effect of background noise did not remain at the perceptual level but interacted actively with the higher levels of linguistic representations via top-down and bottom-up language processing.

Top-down processing, also known as the knowledge-based approach of sentence processing, allows the application of pre-existing linguistic knowledge to facilitate the way the smaller units collected by bottom-up processing are processed (Field, 2004; Goldstein, 2009; Shuai & Gong, 2014; Sohoglu et al., 2012). Bottom-up processing or the data-based approach of sentence processing, on the other hand, relies on the ability to perceive the data from the incoming speech sounds in sentences (or signs if the sentences are in a sign language) and to bind the small units at the lower level of linguistic representation into larger units at the higher level (Field, 2004; Goldstein, 2009; Shuai & Gong, 2014).

An adverse listening condition involving background noise can be an effective method for examining top-down sentence processing. Sentence processing in the presence of background noise requires individuals to rely on their prior knowledge of sentences while having challenges in the bottom-up processing of speech sounds. The bottom-up processing challenge posed by background noise enables the evaluation of subtle difficulties in language processing that are normally not detected under optimal listening conditions. For instance, highly proficient non-native speakers can recognize speech as accurately as native speakers under favorable listening conditions but less accurately under adverse listening conditions (Krizman et al., 2017; Rogers et al., 2006; Scharenborg & van Os, 2019). Specifically, monolinguals performed better in recognizing sentences-in-noise; both monolinguals and bilinguals performed similarly in recognizing words-in-noise; and bilinguals performed better in recognizing tones-in-noise (Krizman et al., 2017). This finding suggests that the monolingual advantage and bilingual disadvantage in sentence recognition in noise are attributable to top-down language processing in noise rather than generic speech perception skills.

Additionally, background noise can increase the dependence on top-down processing. For example, Trecca et al. (2019) hypothesized that listeners need to rely more on top-down processing in noisy situations compared to favorable listening environments. This is due to the compensatory role of top-down processing to restore the degraded speech (Corps & Rabagliati, 2020; Trecca et al., 2019). However, the increase in the dependence on top-down processing can vary depending on the presence of speech degradation, the complexity of speech inputs, and individual differences in long-term linguistic knowledge and processing. Speech degradation (Trecca et al., 2019), simple and predictable forms and meanings of inputs (Corps & Rabagliati, 2020), and robust long-term linguistic knowledge and processing (Rammell et al., 2019) make listeners more likely to rely on their top-down processing during processing sentences in noise.

Depending on how the conditions are manipulated, background noise may be a valuable tool for evaluating SSE in sentence repetition, even in simple sentences, without demonstrating an excessive ceiling effect. SSE is a robust top-down effect that is consistent in challenging conditions (Baddeley et al., 2009; Bonhage et al., 2017; Jefferies et al., 2004; Roverud et al., 2020). In order to determine whether SSE is automated and robust that can be preserved despite the bottom-up processing challenges, it is critical to examine SSE in sentence repetition with background noise. Specifically, I predict that listeners perform significantly better at repeating sentences than at repeating word lists in a favorable listening condition but not in a noisy condition. In a noisy situation, if the top-down morphosyntactic processing that causes SSE is weak and not fully automated, SSE will be reduced by the bottom-up disturbance of background noise.

Neural oscillations

Neural oscillations in sentence processing research

Neural oscillations, the rhythmic electrical activity of the brain over time occurring in different regions (Mathalon & Sohal, 2015), are known to be important in sentence processing (Ding et al., 2016; Meyer, 2018; Prystauka & Lewis, 2019). Research has shown that different frequency bands of brain oscillations synchronize with the timing and units of sentence stimuli and hence reflect on-line sentence processing (Ding et al., 2016; Meyer, 2018). However, it has been debated whether neural entrainment is caused by evoked brain responses due to the rhythmic pattern of acoustic information or by the synchronized activities of neurons in the brain for the internal processing of the information (Meyer et al., 2020). In regard to the debate, Meyer et al. (2020) drew an important distinction between what they referred to as *entrainment proper* and *internal synchronicity*. According to their definition, *entrainment proper* means the evoked neural entrainment caused by the external rhythmic features of stimuli, whereas *internal synchronicity* refers to the endogenous processing of linguistic information at different levels of representation (Meyer et al., 2020).

Recent studies found that while sensory entrainment exists during the stimuli presentation, it does not explain everything about the tracking of linguistic representation. Meyer et al. (2020) argued that neural oscillation is not just an outcome of sensory information because speech is not always rhythmic, and neural synchronization can be found in abstract information processing that does not necessarily involve the rhythmic features of stimuli (Meyer et al., 2020). Kaufeld et al. (2020) also provided evidence that brain oscillations reflect internal processing beyond sensory entrainment. They compared sentences (sentences comprised of real words), jabberwocky (sentences comprised of pseudowords), and wordlists (wordlists comprised of real words). The conditions controlled the acoustic-prosodic and lexical-semantic information. The authors measured mutual information (MI) between speech signals and the brain responses in each condition (Kaufeld et al., 2020). They found that the sentences condition shared the most information with the original speech at the phrasal-level timescale (0.8 – 1.1 Hz) compared to jabberwocky and wordlists. This finding confirmed that neural oscillations reflect more than just sensory responses but demonstrate the different types of internal processing required for different linguistic representations.

The internal synchronicity approach is aligned with research hypothesizing different frequency bands of neural oscillations are associated with different stages and units of language processing. For instance, Meyer (2018) synthesized studies on neural oscillations in speech processing and concluded that the hierarchy of linguistic units in a sentence could be mapped to the degree of the frequency bands in neural oscillations. Generally, the review argued that the higher frequency bands of neural oscillations are more relevant to the processing of smaller units of linguistic representation, and the lower frequency bands reflect the processing of bigger linguistic units. For example, the review summarized that the gamma band (> 30 Hz) oscillations synchronize with phonemes, the theta band (4 – 8 Hz) for syllables, the delta band (0.5 – 4 Hz) for intonational phrasal boundaries.

Meyer’s (2018) theoretical framework serves as feedback and feedforward for many preceding and following studies on the relationship between slower frequency bands of neural oscillations and the processing of higher levels of linguistic representations. The idea especially sheds light on the role of delta-band neural oscillations in syntactic chunking (Bonhage et al., 2017; Ding et al., 2016; Keitel et al., 2018; Lu et al., 2022). Ding et al. (2016) presented Chinese words at a fixed rate so that phrases followed the delta-band frequency. The results showed that there was an activation of the delta-band oscillations in native speakers but not in speakers without knowledge of the language (Ding et al., 2016). Bonhage et al. (2017) also found a greater delta-band (4 Hz) amplitude in the encoding of sentences compared to non-sentences. These findings implied that the activation of the delta-band oscillations in sentence processing reflects the availability and efficiency of syntactic information in sentences.

Another line of research investigates the role of beta band (13 – 30 Hz) in chunking and syntactic processing. (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Davidson & Indefrey, 2007; Schneider et al., 2016; Weiss & Mueller, 2012). These studies did not necessarily posit the direct relationship between different frequency bands and the linguistic hierarchy in language processing. Instead, they focused on the broad role of beta-band neural oscillations in sentence-level syntax and semantics, including syntactic binding in sentence processing. Weiss & Mueller (2012) mentioned in their review that both semantic working memory and syntactic binding might influence the changes in the beta-band oscillations, specifically in the left prefrontal regions. It is difficult to distinguish between sentence-level semantics and syntax due to their tight relationship in sentence processing. To determine whether the beta-band oscillations are truly responsible for syntactic processing, therefore, it is necessary to regulate sentence-level semantics, at least to some extent.

SSE in Brain oscillations

As explained in the section on the sentence superiority effect, the present study is based on the assumption that SSE is primarily driven by morphosyntactic information, with the support of sentence-level semantic information. I also assumed that sentence-level syntactic effects would be stronger than sentence-level semantic effects in SSE based on a prior study demonstrating a smaller contribution of sentence-level semantic effects to SSE than syntactic effects (Massol et al., 2021). Therefore, I hypothesized that the beta-band oscillations observed in the paradigm of SSE would more likely represent morphosyntactic processing than sentence-level semantics.

Earlier studies on the connection between the beta band and SSE have yielded two opposite findings, depending on whether an increase or a decrease in the beta-band power reflects syntactic processing and chunking. Results from earlier research on synchronization vs. desynchronization and the relative power differential between sentences and word lists were mixed (for a review, see Prystauka & Lewis, 2019). Some studies showed beta-power synchronizations, the increase in power compared to the baseline (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Bonhage et al., 2017), whereas other studies showed beta-power desynchronization, the reduction of power relative to the baseline (Lam et al., 2016; Meltzer et al., 2017). Additionally, some studies showed greater power for sentences relative to word lists (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Meltzer et al., 2017), whereas other studies showed the opposite results (Bonhage et al., 2017; Lam et al., 2016).

There are studies showing an increase in the beta-band oscillatory power, or beta-synchronization, in sentences and word lists compared to the baseline. For example, Bastiaansen et al. (2010) found a gradual beta and theta increase for sentences, which was absent for word lists. Also, Bastiaansen and Hagoort (2015) observed an increased beta-band power in sentences with syntactically well-formed structures compared to word lists. Bonhage et al. (2017) also discovered a higher beta power but a relatively greater power in word lists compared to sentences. However, this pattern was observed during the retention phase, not the encoding phase.

Conversely, there are other studies showing a decrease in the beta-band oscillatory power compared to the baseline. Meltzer et al. (2017), for example, found a decreased beta (8 – 30 Hz) for word lists relative to sentences during the retention period. Lam et al. (2016) also showed an overall decrease in power, while the difference between sentences and word lists was the opposite. That is, a greater decrease in power was observed in sentences compared to word lists in the beta-band oscillations (Lam et al., 2016).

Table **1-1**: Previous studies on the relationship between SSE and beta oscillations

	Modality	**Language**	**Lengths**	**Method**	**STM/ WM**	**Freq**	**Results**
Bonhage et al. (2017)	visual	German	6 words	EEG	Retention	Beta-Gamma (27—32Hz)	INC (list > sen)
Bastiaansen & Hagoort (2015)	visual	Dutch	9—11 words	EEG	Encoding	Beta (10—20Hz)	INC (sen > list)
Bastiaansen et al. (2010)	visual	Dutch	6—10 words	MEG	Encoding	Beta (13—18Hz)	INC (sen > list)
Meltzer et al. (2017)	auditory	English	5 words (list) 13 words (sen)	MEG	Retention (recall)	Alpha-Beta (8—30Hz)	DEC (sen > list)
Lam et al. (2016)	visual	Dutch	9—15 words	MEG	Encoding	Beta (14—18Hz)	DEC (list > sen)

Note: STM: short-term memory. WM: working memory. Freq: Frequency band. INC: power increase relative to the baseline. DEC: power decrease relative to the baseline. list > sen: greater power in word lists compared to sentences. sen > list: greater power in sentences compared to word lists.

Table 1-1 shows previous studies on the relationship between SSE and beta oscillations. Note that the selection of the studies in Table 1-1 is based on Prystauka and Lewis (2019)'s review. Among the studies included in the review, I specifically collected studies targeting beta-band oscillations and the comparison between sentence and word lists. Among the five studies included in Table 1-1, Meltzer et al. (2017) present the experimental settings that are most comparable to the present study since it is the only study to contain both auditory stimuli and an immediate verbal recall paradigm.

The present study

Purpose

The purpose of the present study is to examine the behavioral and neurophysiological evidence of SSE in monolingual adults with typical language development. This study aimed to establish the fundamental framework by involving monolingual adults with typical language development for future research on SSE in individuals with DLD. I hypothesize that top-down morphosyntactic processing is an important factor that individuals with DLD have difficulties in their sentence repetition. However, examining on-line morphosyntactic processing is challenging because it is dependent on long-term linguistic knowledge. For example, if the sentences in a sentence repetition test are too simple, the task exhibits a ceiling effect, while if the sentences are too complex, the task reveals more about an individual's long-term linguistic knowledge than online language processing.

Therefore, the current study included SSE and background noise to understand top-down morphosyntactic processing in sentence repetition. I examined SSE to assess how the top-down manipulation significantly improves working memory span compared to word lists consisting of the same lexical items with the same lengths in words. Also, by utilizing a closed set of early acquired vocabulary and a basic and consistent syntactic structure, I aimed to investigate SSE with the minimized impact of long-term linguistic knowledge. I included background noise to confirm if the top-down morphosyntactic processing that causes SSE is robust and automated enough to cope with bottom-up perceptual disturbances. If SSE is not detected in background noise, but only in clear sound settings, this indicates that SSE exists but that the top-down processing driving SSE is not strong enough to overcome speech degradation.

I measured neural oscillations to observe if SSE that was not detected in the behavioral accuracy results can be found in internal neural activities. Due to prior studies supporting the association between the beta band and SSE, the present study focused on the beta band (13 – 30 Hz) among the frequency bands. I also examined the delta-band neural oscillations (1 – 4 Hz) to determine whether SSE may be detected in the slower band of neural oscillations hypothesized to correspond to syntactic phrases in addition to the beta band. The present study measured power (μV^2) in the beta and delta bands. Power refers to an estimate of the amount of energy present in a certain frequency band at a given time point (Cohen, 2014). The increased power in a particular frequency band of neural oscillations is often interpreted as the synchronization or the co-activation of neural activities at a certain time point in a particular brain region (Cohen, 2014).

According to the previous studies on the neural oscillations in SSE, I hypothesized that there would be a significant difference in the oscillatory power changes between sentences and word lists conditions in WLR. However, it was challenging to hypothesize the direction of power changes and the relative power difference between sentences and word lists conditions, given the mixed findings of previous studies (see Table 1-1).

Prystauka and Lewis's (2019) review mentioned studies investigating bindings and sentence comprehension, and many of them showed a general trend of decreasing in the beta band of neural oscillations when stimuli are cognitively challenging to process compared to their less-challenging counterparts. For example, relatively smaller power was observed in no binding condition stimuli compared to binding condition stimuli (Segaert et al., 2018), time-compressed speech relative to intact speech (Pefkou et al., 2017), reversible sentences than non-reversible sentences (Meltzer & Braun, 2011), and object-relative sentences than subject-relative sentences (Meltzer & Braun, 2011). Therefore, if the word lists condition in WLR was more cognitively demanding than the sentences condition, relatively less oscillatory power would be observed in word lists than in sentences. Furthermore, the overall power in both sentences and word lists would exhibit a decreasing trend relative to the baseline period if the stimuli of both conditions were cognitively demanding.

Research questions

Research Question 1: Does behavioral accuracy in word list recall show differences between sentences and word lists moderated by noise?

Research Question 2: Do the beta-band neural oscillations in word list recall show differences between sentences and word lists moderated by noise?

Research Question 3: Do the delta-band neural oscillations in word list recall show differences between sentences and word lists moderated by noise?

Research Question 4: Are the beta- and delta-band neural oscillations in word list recall associated with sentence repetition?

Chapter 2

Methods

Participants

I recruited participants through flyers, Penn State StudyFinder, and email listserv. A total of twenty-seven participants participated in the study. Participants were adults 18 years of age or older who were all native speakers of English. Among the twenty-seven participants, four participants were not included in the data analysis. One bilingual participant who was conversationally fluent in a language other than English was excluded; one participant was excluded due to extremely high impedance level of EEG channels during the experiment; one participant was excluded due to relatively high age compared to other participants; and one participant was excluded due to a history of brain injury. Consequently, twenty-three participants were included in the analysis.

A power analysis was conducted using G*Power (Faul et al., 2007) to calculate the target number of participants. A sample size of 19 for large effect and 45 for medium effect was computed for *t*-tests. The current study's sample size (n = 23) falls between the medium and large effect sizes. In addition, the size of the sample is typically considered acceptable in previous EEG studies using similar experiments and statistical methods (Bastiaansen et al., 2010; Bonhage et al., 2017; Meltzer et al., 2017).

All participants included in the analysis were right-handed, without a history of hearing impairment or neurological disorders for EEG experiment. The participant recruitment and consent processes were approved by the Institutional Review Board for human subjects research at the Pennsylvania State University.

Electroencephalography measures

Word list recall (EEG version)

This dissertation project used an adapted version of sentence repetition, a *word list recall* task, instead of natural sentences. The word list recall adopted and modified the task paradigm of Baddeley et al. (2009), in terms of the length of each list (eight words) and the method of comparing word lists with and without sentence structure. The word list recall was similar to sentence repetition but with 2 x 2 within-subjects conditions by manipulating the existence of sentence structure and background noise. See Table 2-1 for a schematic of the design.

Table **2-1**: Examples of word list recall stimuli

		The sentence superiority effect	
		Sentence structure (+)	Sentence structure (-)
Energetic masking (White noise)	Noise (-)	*big, friend, is, washing, coat, and making, juice* [masking off]	*making, washing, friend, juice, is, coat, big, and* [masking off]
	Noise (+)	*big, friend, is, washing, coat, and making, juice* [masking on]	*making, washing, friend, juice, is, coat, big, and* [masking on]

A total of 120 stimuli was used. Each condition consisted of 30 stimuli, and each stimulus was eight words in length (three nouns, one adjective, one auxiliary verb ("*is*"), one conjunction ("*and*"), two verbs with a present progressive form ("-*ing*"). To minimize lexical effects, the words in the stimuli were early vocabulary derived from the MacArthur-Bates Communicative Development Inventories (CDIs; Fenson et al., 2007) and early vocabulary words from Kuperman et al. (2012) and Łuniewska et al. (2019).

On each trial, participants listened to a list of eight words presented auditorily at a rate of one per second. Figure 2-1 shows a schematic of list construction.

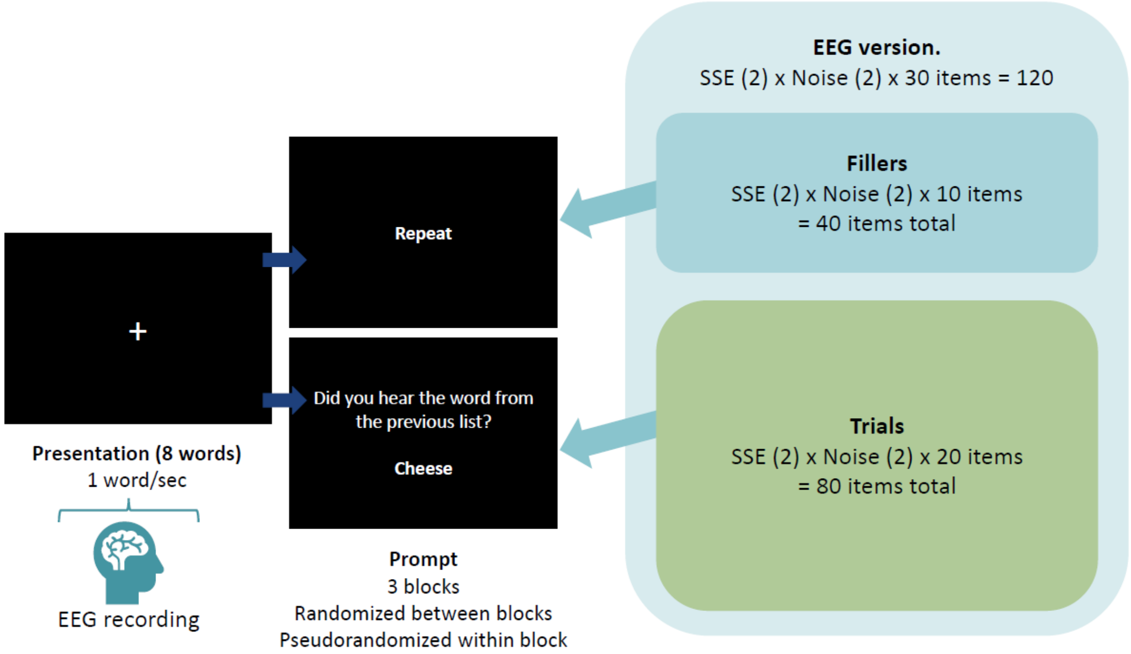


Figure **2-1**: The construction of word list recall (EEG version)

Participants were asked to listen to and remember the list of eight words as best they could. After each list, participants were asked to either repeat the preceding item or to judge whether a word presented on the screen was included in the previous list of words (See Figure 2-2). The assignment of trials to repetition or judgment conditions was determined pseudo-randomly, with the constraint that all the repetition and judgment trials were initially randomized and assigned to each block. The randomized order of trials was fixed after their assignment to each block. The presentation order between blocks was randomized per participant. Thus, participants were required to prepare to remember and repeat the word lists on every trial, since they could not predict when full repetition would be required. 120 items in total were divided into three blocks and were presented in random order.

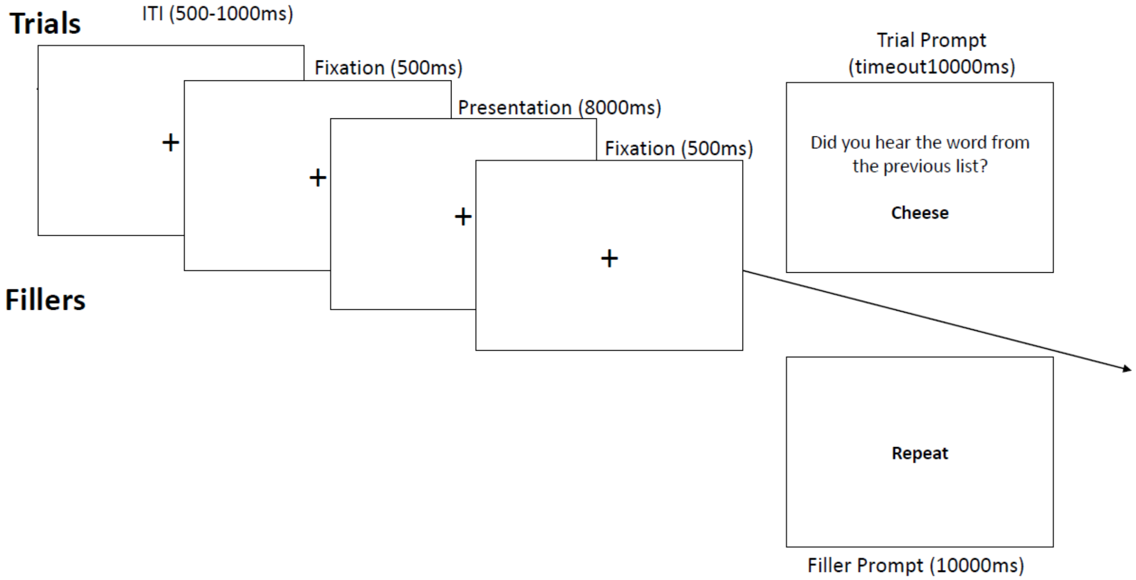


Figure **2-2**: The timeline of word list recall (EEG version) presentation

Sentence structure

For the word lists with sentence structure, we used a sentence structure comprised of one subject-noun phrase (NP subject) and two verb phrases (VP) combined with a conjunction "*and*", with a present progressive tense, making a list to be divided into three phrases (NP, VP1, VP2). The NP subject was modified by an adjective, and each verb phrase consisted of one transitive verb, one object noun, and one adjective modifying the object noun. All the strings in the word lists with sentence structure were presented in the same order (e.g., *big-friend-is-washing-coat-and-making-juice*).

For the word lists without sentence structure, we used the same words in the word list with sentence structure but scrambled the words within each stimulus. The entire scrambled order word list was presented with the same following order: *verb-verb-noun (agent)-noun (theme)-auxiliary "be"-noun (theme)-adjective-conjunction* (e.g., *making-washing-friend-juice-is-coat-big-and*).

The designated structure of the scrambled order was consistent for all trials. It was possible that participants might learn the designated structure of the scrambled word lists due to its repetitive occurrence during the experiment. However, we expected the repetition effect to be minimal because the word lists were randomly presented and both word lists with and without sentence structure followed their designated sequences. Each scrambled sequence corresponded to each item with sentence structure sequence that was comprised of the same words. By using the same words in both conditions, possible semantic factors derived from the lexical items that could affect the performance were matched across the conditions.

Noise

For the word lists with noise, white noise masking was presented with word lists. The average intensity of signal sounds was 65 dB SPL and the average intensity of background noise was 61 dB SPL to get the average of + 4 dB SNR. For the word lists without noise, no energetic masking was included.

Stimuli recording and editing

Recordings of words were done by a female monolingual native speaker of English, in a quiet place using Marantz PMD-660 audio recorder. Sound editing was done by using Praat (Boersma, 2001). The sampling frequency (Hz) was 48000 Hz and the intensity was adjusted to 65 dB SPL. The recordings were divided word-by-word, concatenated to construct sentences and word lists using Praat scripts. The duration of each list (8 seconds) and the acoustic features of words in each condition were the same because the two conditions were derived from the same recording of words. For constructing the background noise condition, a white noise sound that has the same duration with a word list (8 seconds) was created by using a randomGauss function with a zero mean and 0.1 standard deviation, and the intensity was adjusted to 61dB SPL. The white noise was then added to sentences and word lists files to make the conditions with background noise.

Behavioral measures

Word list recall (behavioral version)

One third of the stimuli used in the EEG version of word list recall was used to construct a behavioral version of the same task. The design of the task was the same as the EEG version except that the behavioral version did not have a judgment prompt asking if a word was included in the previous list of words; that is, participants repeated the word lists on all trials.

Sentence repetition

An adapted version of a sentence repetition task (Poll et al., 2016) was used for the study. The study included 24 sentences. Among 24 sentences, half of the sentences were argument-laden, and the other half of the sentences were adjunct-laden. Although the task includes both short (16 syllables) and long sentences (25 syllables), only the 24 short sentences were included in the analysis due to the participants' overall poor performance on the long sentences.

Digit span

Forward (FWD) and backward digit span (BWD) were used for measuring short-term and working memory, respectively. The tasks were adapted from the Digit Span subtest of Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV; Wechsler, 2008), but standardized norms were not used for analyses. The examiner first started with FWD, read a set of number sequences, and asked the participant to repeat the number sequence in the same order. For BWD, the examiner asked the participant to repeat the item sequences backwards. Each item consists of two trials. For FWD, there were 16 trials in total, from two-digit to nine-digit items with two trials at each span length. For BWD, there were 14 trials in total, from two-digit to eight-digit items with two trials at each span length. If the participant failed to remember the target sequence on both trials of any item, the examiner discontinued the task. Raw scores were used for the analysis.

LexTALE

The Lexical Test for Advanced Learners of English (LexTALE, Lemhöfer & Broersma, 2012) is a lexical decision task comprised of 60 trials in total. The task requires participants to determine if a string of letters is an existing English word in each trial. There are 40 real words and 20 nonwords. The present study used the LexTALE scoring method recommended by Lemhöfer and Broersma (2012), due to its high sensitivity when measuring English proficiency. The LexTALE score calculation is displayed below. The purpose of this calculation is to measure the averaged percentage of correct answers, because the number of real words and nonwords are different.

LexTALE score = ((Number of real words correct/40*100) + (Number of nonwords correct/20*100))/2

Picture naming

Picture naming (Beatty-Martínez et al., 2020) is a lexical retrieval task that requires a verbal production of each word. There are Spanish and English versions of the task in the previous study (Beatty-Martínez et al., 2020); however, the present study only used the English version because the participants of the study were English-speaking monolinguals. There were 66 black and white line-drawing pictures shown on a monitor sequentially. Before each picture, there was a blank transition screen with a fixation point (“+”) in the middle. Participants were instructed to press the spacebar to proceed with the next trial. Participants named picture in English as quickly and accurately as possible. Once the voice key was activated by the participant's voice through the microphone in front of the participant's mouth, the image disappeared from the screen and the next blank transition screen was presented.

The inclusion and exclusion criteria for measuring reaction times (RTs) were based on the previous study (Beatty-Martínez et al., 2020). RTs for correct responses were included in the analysis. RTs involving registration errors (e.g., repetition of words, cough) were excluded. Also, RTs below 300ms or above 2000ms were excluded. After that, all RTs that deviated by more than 2.5 standard deviations from the mean of each participant were likewise excluded from the data.

Procedure

The first visit took around one and a half hours and the second visit two hours. During the first visit, consent procedures and behavioral tasks were completed. During the second visit, participants were capped with the EEG electrodes, and cortical activity was measured during completion of the experimental tasks. At the first visit, participants responded to questions regarding their history relevant to language-related learning disability, a language background questionnaire adapted from the language history questionnaire (LHQ 3.0; Li et al., 2020), and demographics and handedness. The participant's head size was measured for choosing a suitable EEG cap to be used at the second visit. Participants completed behavioral language and memory tasks: A behavioral version of word list recall to measure SSE in behavioral results, sentence repetition task (Poll et al., 2016) to measure the performance of typical sentence repetition, LexTALE to measure language proficiency, picture naming to measure lexical retrieval proficiency in the verbal production of words, and forward and backward digit span tests to measure short-term memory and working memory, respectively. The voice recordings of these tasks were manually transcribed for behavioral analysis after the experiment.

At the second visit, EEG responses were recorded during the experiment and behavioral responses were recorded through a voice recorder placed in the chamber. Participants were seated in a comfortable chair in a sound-attenuated dimmed room, approximately three feet away from a computer monitor and speakers on which the stimuli were presented. An elastic cap (BrainProducts ActiCap) with 30 active Ag/AgCl electrodes was placed on the head: four electrodes located along the midline (Fz, Cz, Pz, Oz) and 26 electrodes on the lateral sites (FP1/2, F7/8, F3/4, FC5/6, FC1/2, FT9/10, T7/8, C3/4, CP5/6, CP1/2, P7/8, P3/4, and TP9/10 on left and right mastoid). Figure 2-3 shows the electrode montage. Additional electrodes were placed below the left eye and at the outer canthus of the right eye, to screen for ocular artifacts. EEG signals were amplified by a BrainVision ActiCHAMP amplifier digitized with a 500 Hz sampling rate. Electrodes were referenced to the right mastoid (TP10). Participants listened to a set of word lists and prepared to repeat the lists verbatim. E-Prime 3.0 was used for stimuli presentation. All the 120 items were used for the EEG analysis, while only 40 items were selected to be repeated verbatim, the same items that were used in behavioral version of word list recall, which were not included in the EEG analysis of word list recall. The purpose of using only one-third of items for repetition was to minimize the experiment duration and participant fatigue and to reduce potential orofacial movement artifacts caused while repeating items. Analyses were conducted on EEG activity during the presentation period of each trial (8000 ms) and did not include the response period, as the activity during repetition itself will be contaminated by movement. The procedure was approved by the University's Institutional Review Board.

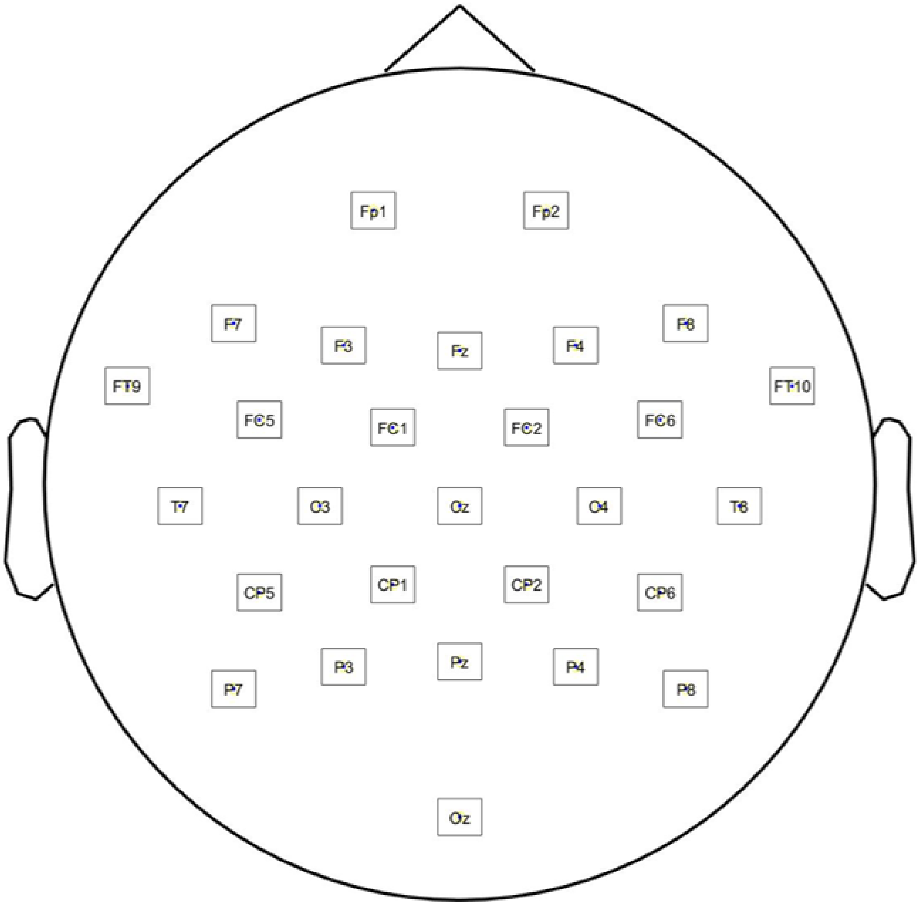


Figure **2-3**: Channel location (28 channels, based on EEG1010 layout)

EEG data processing

I used EEGLAB toolbox (Delorme & Makeig, 2004) and ERPLAB plugin in MATLAB (The MathWorks, Inc) for data preprocessing. I used a bandpass filter between 0.5 Hz and 30 Hz. While the target duration of stimuli presentation for the analysis is from 0 ms to 8000 ms, the time duration of each epoch was between -2000 ms and 10500 ms with its baseline correction using the baseline between -500 ms and 0 ms. I set an epoch duration wider than the target duration to prevent the time cut-off as a result of calculating time-frequency representations. The epoch duration physically overlapped with the preceding and following items, but the overlap did not affect the analysis because the result contained only the target presentation time after the time-frequency transformation.

Noisy channels were rejected by visual inspection and interpolated by a spherical interpolation method. Only T7 and T8 were shown as noisy for a few participants. Specifically, Electrode T7 and T8 were rejected and interpolated from the data of three participants, T7 from the data of one participant, and T8 from the data of one participant. Except for the five participants' data, no other channel rejection was conducted. The data collection mostly occurred in early 2022, when indoor masking was required for participants and experimenters participating in in-person experiments under a research guideline preventing COVID-19. During the data collection, we found the locations of T7 and T8 sometimes physically overlapped with the location of the mask straps and assumed that this overlap can be the reason for the noisy T7 and T8 for some participants.

Eye blinks and noisy components were removed using independent component analysis (Delorme & Makeig, 2004) and ICLabel plugin (Pion-Tonachini et al., 2019) in EEGLAB. Less than 10% of the total number of ICs (up to three ICs) were removed from each participant’s data. I rejected eye-movement and noisy ICs between IC 1 and IC 10 that did not contain a “Brain” component accounting for more than 10% of the variance. The ICLabel plugin function organized ICs in the order of percent data variance accounted for. Therefore, eye movement and noisy ICs with a smaller component number were more likely to disrupt the data quality. Remaining noisy epochs were rejected using artifact detection targeting -500 ms and 8000 ms of time window, the target duration of the analysis. I applied a simple voltage threshold of +/- 500 mV, aimed to 5-10 % rejection (Delorme et al., 2007). Channels for eyes and mastoids were rejected.

After the preprocessing, each EEGLAB set file was divided into four conditions. The EEGLAB set files were then converted to the FieldTrip toolbox (Oostenveld et al., 2011). Time-frequency representations (TFRs) of power (μV^2) were calculated using Hanning tapers between 1 Hz and 30 Hz in steps of 0.5 Hz, and times between 0 and 8 seconds in steps of 0.05 seconds with 3 cycles per time. After the transformation, the time-frequency structures were averaged per condition.

A non-parametric cluster-based permutation with an alpha cluster threshold of 0.05 was used to compare the main and interaction effects statistically. The cluster-based permutation identified clusters showing significant differences between conditions by selecting and combining adjacent timepoints, frequency points, and channels showing significant differences. The triangulation method was used to identify cluster neighbors for channels. The significance probability of each cluster was calculated by the Monte Carlo method. The Monte Carlo method randomly selected and reassigned the trials of different conditions and calculated the summed adjacent t values. The previous steps were repeated for a substantial number of iterations (N = 5000) to increase the accuracy of the approximation.

Chapter 3

Results

Descriptive statistics

Descriptive statistics were calculated to describe participants' demographic information (see Table 3-1).

Table **3-1**: Participants' demographic information

Demographic information	Statistics
Age (years)	
Mean (*SD*)	26.61 (2.73)
Range (min-max)	19–66
Age group (years)	Frequency (n (%))
19-29 years old	18 (78.26 %)
30-39 years old	1 (4.35 %)
40-49 years old	2 (8.70 %)
50 years old or older [a]	2 (8.70 %)
Gender	Frequency (n (%))
Female	17 (73.91 %)
Male	5 (21.74 %)
Prefer not to say	1 (4.35 %)
Highest education level	Frequency (n (%))
High school diploma or equivalency [b]	16 (69.57 %)
Bachelor's degree	3 (13.04 %)
Student in a graduate degree program	1 (4.35 %)
Master's degree	2 (8.70 %)
Doctoral degree	1 (4.35 %)

Note: Min: Minimum statistic. Max: Maximum statistic

[a] The data from one participant with the maximum age among the current participants (66 years old) was included in the analysis because the participant's data were not shown as extreme outliers (± 3 SD) of any of the behavioral and EEG experimental results.

[b] High school diploma or equivalency also includes participants who are students in a 4-year college or university.

SSE in the behavioral accuracy

The main effect of SSE was significant (*F* (1, 22) = 113.24, *p* < .001). The sentences (+ SSE) condition showed a higher accuracy compared to the word lists (- SSE) condition. The effect of noise was also significant (*F* (1, 22) = 89.36, *p* < .001). The conditions without noise (- Noise) showed a higher accuracy compared to the noisy condition (+ Noise). The interaction effect between SSE and noise was not significant (*p* > .05). Figure 3-1 shows the accuracy (%) of the behavioral word list recall.

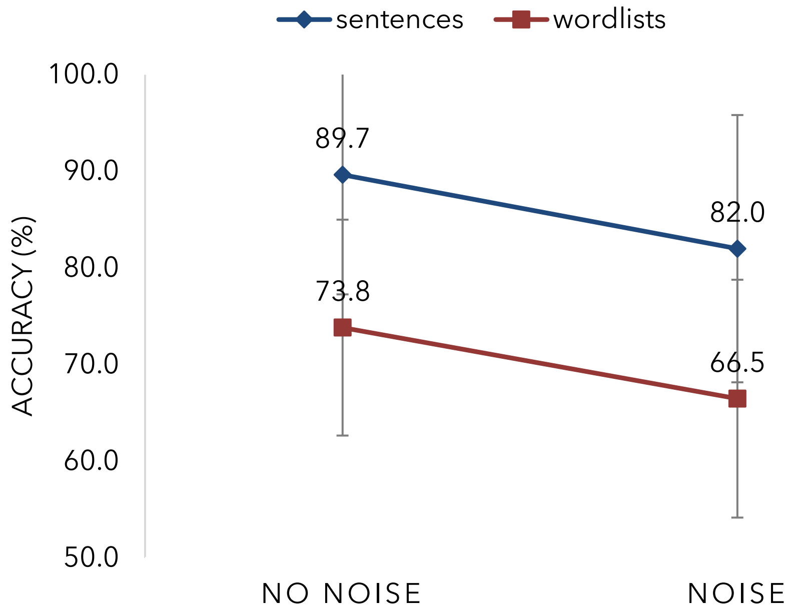


Figure **3-1**: The accuracy (%) of the behavioral word list recall

SSE in neural oscillations

SSE in the beta-band (13 – 30 Hz) neural oscillations

The nonparametric cluster-based permutation analysis indicated the effect of SSE within the beta band (13 – 30 Hz). This corresponds to two clusters: one between 6 and 6.9 seconds ($p < .005$) and another between 7 and 7.55 seconds ($p < .005$) from the onset (0 seconds) of each list. The two clusters were found in all the channels (28 channels in total) with all the frequency points included in the beta band (13 – 30 Hz). The sentences condition (+ SSE) showed a greater beta power change compared to the word lists condition (- SSE) in both clusters (Cluster 1: $M_{\text{difference}} = 0.51$, $SD = 0.96$; Cluster 2: $M_{\text{difference}} = 1.12$, $SD = 2.65$). $M_{\text{difference}}$ was calculated by subtracting the average of the power change in the word lists condition from the average of the power change in the sentences condition.

Figure 3-2 shows the two beta-clusters in the time-frequency representation of one electrode (Fz). Figure 3-3 displays the first cluster showing beta-band power changes compared to the baseline period (-0.5 – 0 seconds) across channels between the sentences and the word lists conditions. Figure 3-4 shows the beta power changes in the second cluster. The time period of the clusters corresponds to the presentation of the last two words (See Figure 3-5).

No clusters in the beta band for the effect of noise and the interaction effect between SSE and noise reached the significance level ($p > .05$).

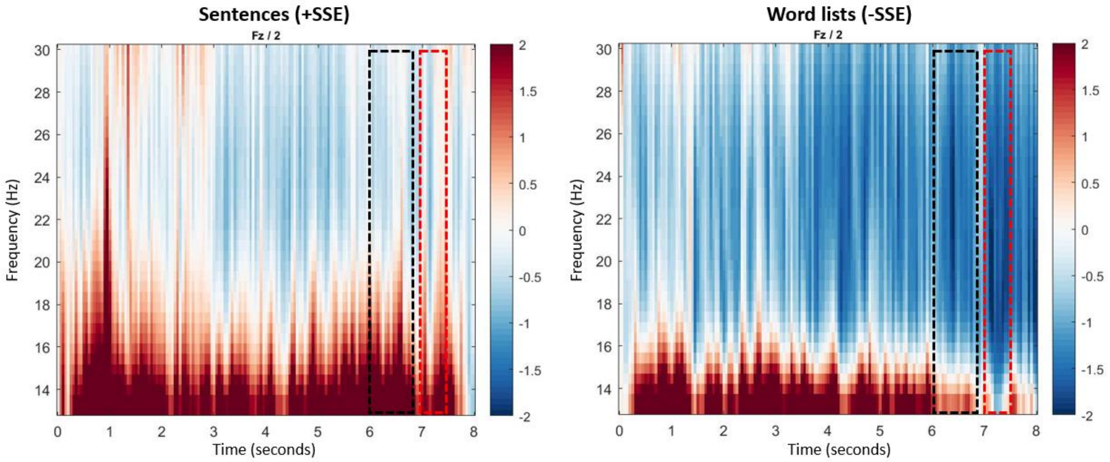


Figure **3-2**: Time-frequency representations of an electrode (Fz) showing beta power (μV^2) changes

Note: The black dotted rectangle shows the first cluster (6 – 6.9 seconds), and the red dotted rectangle shows the second cluster (7 – 7.55 seconds).

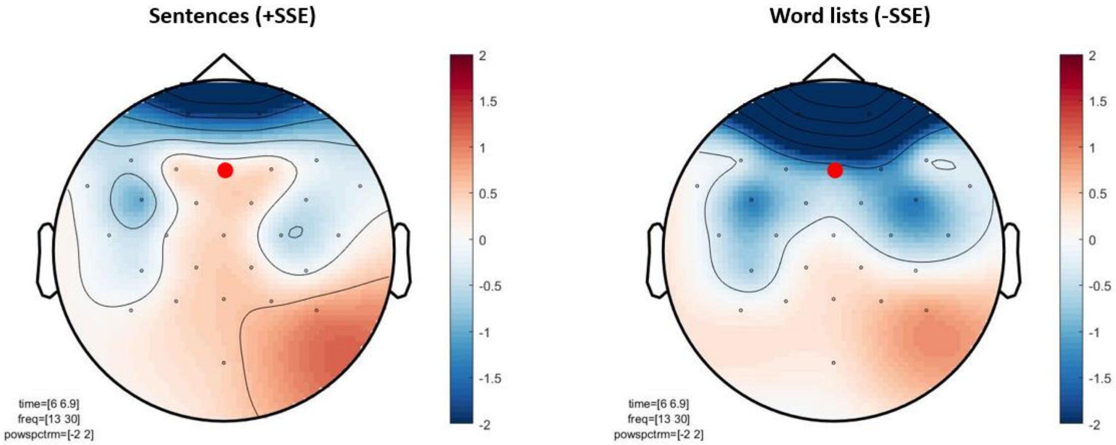


Figure **3-3**: A scalp map showing the first cluster (6 – 6.9 seconds) in the beta band

Note: The red dot shows the location of Fz.

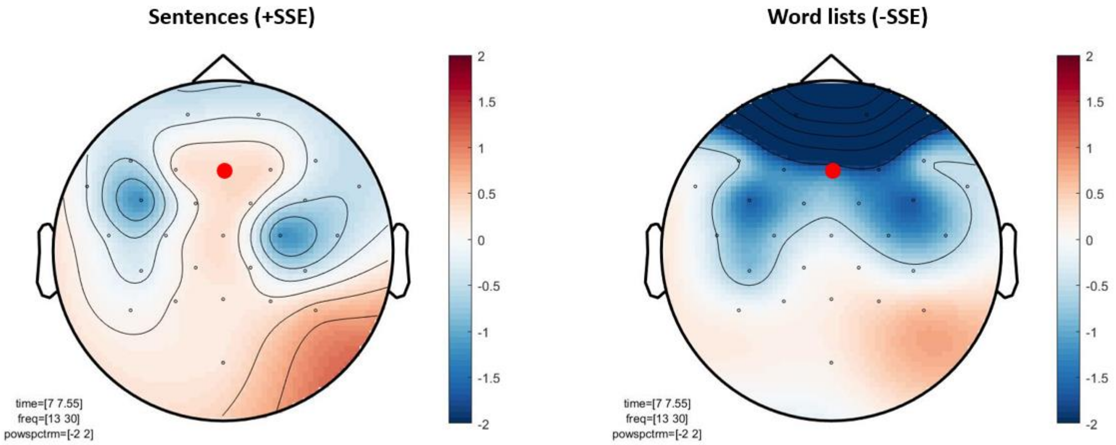
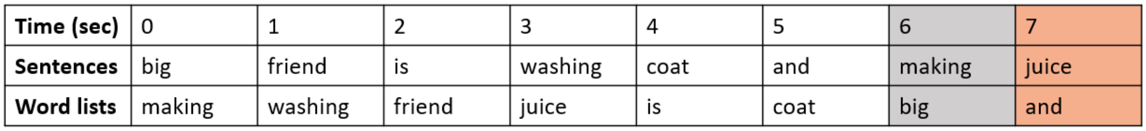


Figure **3-4**: A scalp map showing the second cluster (7 – 7.55 seconds) in the beta band

Note: The red dot shows the location of Fz.



Time (sec)	0	1	2	3	4	5	6	7
Sentences	big	friend	is	washing	coat	and	making	juice
Word lists	making	washing	friend	juice	is	coat	big	and

Figure **3-5**: The time period of the first (gray) and the second (orange) clusters in the beta band

Note: The second and third rows show examples of sentences and word lists.

SSE in the delta-band (1 – 4 Hz) neural oscillations

The nonparametric cluster-based permutation analysis indicated SSE within the delta band (1 – 4 Hz). This corresponds to one cluster: between 6.45 and 8 seconds ($p < .0005$) from the onset of each list (0 seconds) in all the channels except for Fp1 (27 channels in total) with all the frequency points included in the delta band (1 – 4 Hz). The sentences condition (+ SSE) showed a greater delta power change compared to the word lists condition (- SSE) in the cluster ($M_{\text{difference}} = 0.55$, $SD = 0.90$).

Figure 3-6 shows the delta-cluster in the time-frequency representation of one electrode (Fz). Figure 3-7 displays the cluster showing delta-band power changes compared to the baseline period (- 0.5 – 0 seconds) across channels between the sentences and the word lists conditions. The time period of the delta cluster corresponds to the presentation of the last two words of each sentence/word list (See Figure 3-8).

No clusters in the delta band for the effect of noise and the interaction effect between SSE and noise reached the significance level ($p > .05$).

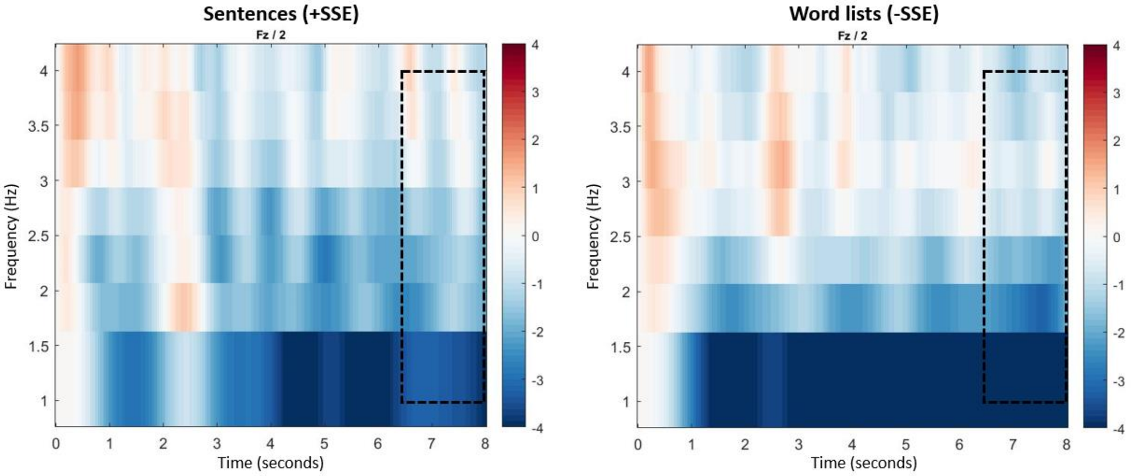


Figure **3-6**: Time-frequency representations of an electrode (Fz) showing delta power (μV^2) changes

Note: The black dotted rectangle shows the cluster (6.45 – 8 seconds).

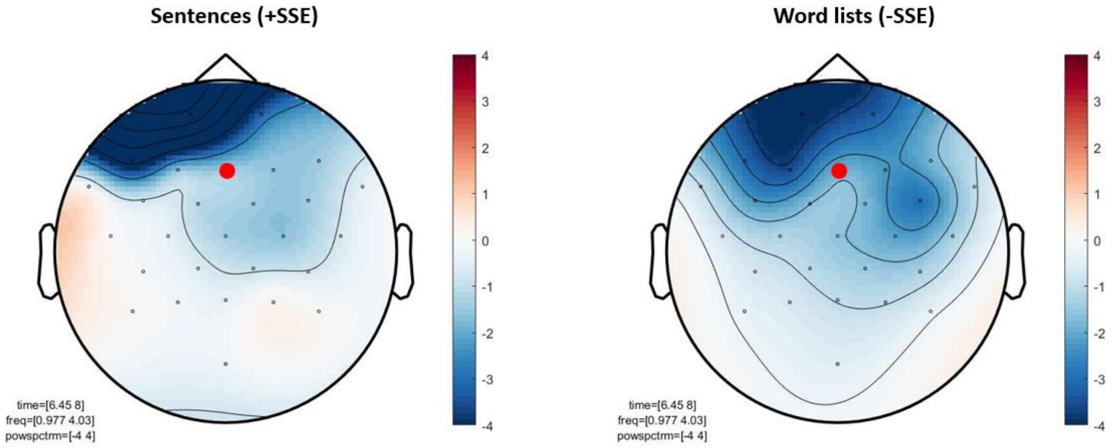
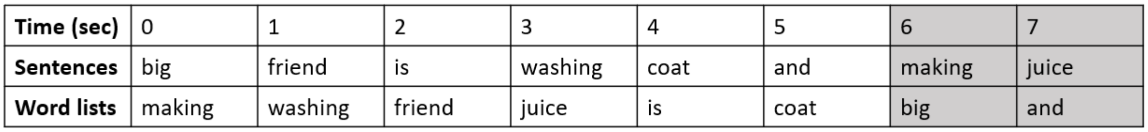


Figure **3-7**: A scalp map showing the cluster (6.45 – 8 seconds) in the delta band

Note: The red dot shows the location of Fz.



Time (sec)	0	1	2	3	4	5	6	7
Sentences	big	friend	is	washing	coat	and	making	juice
Word lists	making	washing	friend	juice	is	coat	big	and

Figure **3-8**: The time period of the cluster in the delta band (gray)

Note: The second and third rows show examples of sentences and word lists.

The association between word list recall and sentence repetition

First, a Pearson correlation coefficient was computed to examine the correlation between word list recall, sentence repetition, and other cognitive-linguistic variables. The mean power changes were extracted from a significant cluster in the beta and delta band respectively. Since there were two significant clusters in the beta band, the first cluster was selected to represent the beta-band activities. There was a significant positive correlation between sentence repetition and the behavioral accuracy of word list recall sentences (r (21) = .74, p < .01) and word lists (r (21) = .78, p < .01), LexTALE scores (r (21) = .52, p < .05), digit span forward (r (21) = .63, p < .01), and digit span backward (r (21) = .54, p < .01). Also, there was a significant negative correlation between sentence repetition and the oscillatory power changes in the delta band sentences (r (21) = -.56, p < .01) and word lists (r (21) = -.63, p < .005). While beta-band oscillations also showed a negative correlation with sentence repetition, the coefficient was not statistically significant at the alpha level of .05 for both sentences (r (21) = -.41, p > .05) and word lists (r (21) = -.41, p > .05). No significant correlation was found between sentence repetition and SSE, the oscillatory power difference between sentences and word lists, in either beta (r (21) = .001, p > .05) or delta bands (r (21) = .17, p > .05). See Table 3-2 for the correlation coefficients. In terms of WLR, only the sentences condition was included in the table for both behavioral and EEG results for clarity.

Table **3-2**: The correlation coefficients between sentence repetition, word list recall, and other cognitive-linguistic variables

	WLR_sen	beta	delta	LexTALE	PN_RT	FWD	BWD
SenRep	.74**	-.41	-.56**	.52*	-.08	.63**	.54**
WLR_sen		-.16	-.09	.52*	-.32	.60**	.55**
beta			.64**	-.27	.36	-.20	-.36
delta				-.26	-.02	-.20	-.23
LexTALE					-.31	.53**	.26
PN_RT						-.05	-.14
FWD							.58**

* $p < .05$. ** $p < .01$.
Note: SenRep: sentence repetition accuracy. WLR_Sen: word list recall sentences condition behavioral accuracy. beta: beta-band power changes in sentences condition in the first cluster. delta: delta-band power changes in sentences condition in the cluster. PN_RT: picture naming reaction time. FWD: digit forward, BWD: digit backward.

Multiple linear regression was conducted to see the association between word list recall and sentence repetition. Sentence repetition scores were included as a dependent variable. Due to the large number of variables in word list recall, I selected sentences condition variables for the regression model while excluding word list condition variables and the oscillatory power difference between sentences and word lists. The word lists condition was excluded from the model due to its strong correlation with the sentences condition. The oscillatory power difference between sentences and the word list was also excluded from the model since, according to the correlation data, it was not associated with sentence repetition. Consequently, the mean power changes of the first cluster in the beta band in sentences condition, the mean power changes of the cluster in the delta band in sentences condition, the behavioral accuracy of word list recall sentences condition, FWD and BWD, LexTALE accuracy, and the picture naming reaction time (RT) were included as the independent variables of the model. The model significantly predicted sentence repetition (R^2 = .83, R^2adjusted = .76, F (7,15) = 10.75, p < .001). The results of the regression indicated that the behavioral version of word list recall sentences condition accuracy (β = .64, p < .001) and the delta-band power (β = -.44, p < .05) significantly predicted sentence repetition. Table 3-3 shows the multiple regression model.

Table **3-3**: The multiple regression model predicting sentence repetition

	B	*SE*	β	*t*	*p* value
(Intercept)	-51.44	34.46		-1.49	.16
WLR_Sen	.91	.22	.64	4.10	< .001***
beta	-.20	.89	-.04	-.22	.83
delta	-2.37	.82	-.44	-2.90	.011*
LexTALE	.09	.28	.04	.31	.76
PN_RT	.02	.02	.15	1.14	.27
FWD	.92	1.14	.13	.81	.43
BWD	.07	.99	.01	.07	.95

* p < .05. *** p < .001.
Note: SenRep: sentence repetition accuracy. WLR_Sen: word list recall sentences condition behavioral accuracy. beta: beta-band power changes in sentences condition in the first cluster. delta: delta-band power changes in sentences condition in the cluster. PN_RT: picture naming reaction time. FWD: digit forward. BWD: digit backward.

Chapter 4

Discussion

The present study analyzed the behavioral and electrophysiological patterns of the sentence superiority effect in sentence repetition with and without background noise. The study also examined the association between sentence superiority effect and sentence repetition. This section discusses the interpretation of the findings and their research and clinical implications.

SSE in behavioral accuracy

There were significant main effects of SSE and noise, but no significant interaction effect was found in the behavioral accuracy of word list recall. Unlike the hypothesis, the effect of SSE did not vary depending on the presence of background noise. There are at least two possible explanations for the absence of the interaction effect.

First, the intensity of the noise was mild compared to the signal sound, so the SNR of the noisy condition is quite high. The average intensity of signal sounds was 65 dB SPL, and the average intensity of background noise was 61 dB SPL to get the average of + 4 dB SNR. Therefore, the absence of interaction between SSE and noise might be due to the mild level of energetic masking in the noisy condition.

However, there was still a significant main effect of noise, implying that noise interfered with the precise repetition of words. The significant main effect of noise with the absence of the interaction effect with SSE may be related to the scoring method employed in the present study. The behavioral word list recall score was based on the number of correctly responded words. The errors included phonologically incorrect words. For example, phonological errors such as “hiding” instead of “biting,” “picking” for “kicking,” and “low” for “slow” were often found in the background noise condition of word list recall. In the noisy condition, white noise seems to disturb the perception of some onset consonants. Because these phonological errors were also counted as errors, the accuracy in the noisy condition can be substantially reduced. Additionally, the technique did not consider word transpositions as errors. Therefore, a scoring method that penalizes syntactic deviations, such as word transposition errors, more than phonological errors may reveal more about SSE and thus exhibit the interaction between SSE and noise in the word list recall behavioral accuracy.

SSE in neural oscillations

The present study observed the main effects of SSE in the beta and delta band, primarily for the last two words of each eight-word presentation. No clusters in the effect of noise or the interaction between SSE and noise reached the significance level.

Power differences between sentences and word lists

The greater power changes in the beta band of sentences compared to word lists were consistent with previous findings (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Meltzer et al., 2017). Also, the greater power changes in the delta band of sentences relative to word lists were in line with the previous studies (Bonhage et al., 2017; Kaufeld et al., 2020; ten Oever et al., 2022).

The results of the present study were not consistent with a different line of studies showing a greater beta-band power in word lists compared to sentences (Bonhage et al., 2017; Lam et al., 2016). The different results may be due to the differences in the range of the target frequency bands between the present study and the two previous studies. Specifically, the frequency ranges targeted by the previous two studies partially overlapped with but were distinct from those of the present study. Bonhage et al. (2017) focused on the beta-gamma band between 27 Hz and 32 Hz, and Lam et al. (2016) focused on the lower beta band between 14 Hz and 18 Hz, which were both narrower and different from the frequency range used in the current study (13 – 30 Hz).

In addition, the different results may be attributed to the use of different baselines. Prystauka and Lewis (2019) stated that Meltzer et al. (2017) and Bonhage et al. (2017) may have obtained inconsistent results because of their differences in the baselines. Both the current study and Meltzer et al. (2017), which found comparable results for the greater decline of the beta-band power in word lists compared to sentences, used the pre-stimulus interval as the baseline. Specifically, the present study employed - 0.5 seconds to 0 seconds as the baseline for the time-frequency analysis, whereas Meltzer et al. (2017) used - 3.7 seconds to - 0.2 seconds. In contrast, Bonhage et al. (2017) utilized the end of the encoding period as the retention period baseline. Lam et al. (2016) used the average of two time periods centered at - 150 and - 100 ms after the subtraction of the pre-stimulus baseline period. Therefore, I expect future studies using the same baseline period of the pre-stimulus interval between - 0.5 and 0 seconds may yield results consistent with the present study.

Decreased power in sentences and word lists

The power changes of the present study showed a decreased power in both the beta (13 – 30 Hz) and the delta band (1 – 4 Hz) compared to the baseline period (- 0.5 – 0 seconds), with a greater decrease of the word lists condition compared to the sentences condition. The results were consistent with Meltzer et al. (2017), demonstrating a decrease in beta-band power in sentences accompanied by a greater power decrease in word lists compared to sentences. The result is also consistent with a study showing decreased beta-band power in the ungrammatical condition compared to the grammatical condition (Schneider et al., 2016).

The results did not correspond to the previous studies demonstrating an increase in power of the beta-band (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015) and delta-band (Bonhage et al., 2017) oscillations with a greater power increase for sentences than word lists. However, the studies showing increased power in the beta or delta band used a visual modality with a word-by-word presentation (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Bonhage et al., 2017), whereas the studies demonstrating a decrease in the beta and delta power involved an auditory presentation of the stimuli (Meltzer et al., 2017; Schneider et al., 2016). Therefore, using auditory stimuli and targeting the same frequency bands (13 – 30 Hz) may enable future studies to replicate the findings of the present study.

SSE in neural oscillations and chunking

In the present study, clusters that reached the significant threshold in the beta and delta band were found in the final two words of the eight-word presentation. The results are in line with Cowan's hypothesis on chunking, saying that the short-term memory span is limited to 4 ± 1 chunks (Cowan, 2001, 2010). According to Cowan (2001, 2010), there should be no significant differences in memorizing the words in sentences versus in word lists for the first five words. In terms of timing, therefore, it is reasonable to assume that the genuine SSE may be discovered in the memorization of words, at least after the presentation of the first five words. This is one of the many benefits of utilizing EEG to measure SSE, as it allows for the observation of the precise timing of SSE within an individual's internal language processing.

The association between SSE and sentence repetition

The behavioral accuracy of word list recall sentences condition and the delta-band cluster in sentence condition between 6.45 and 8 seconds significantly predicted sentence repetition performance. While the association was not significant when directly involving SSE, the difference between sentences and word lists, the results are aligned with the hypothesis of the current study that online morphosyntactic processing is relevant to sentence repetition performance.

The positively significant association between the behavioral version of word list recall and sentence repetition means that a person showing a higher accuracy in word list recall sentences is likely also to demonstrate a higher accuracy in sentence repetition. The association is plausible given that the administrations of sentence repetition and word list recall sentences condition are nearly identical, despite the fact that word list recall consists of a closed set of words lacking sentence intonation.

The negatively significant association between the delta-band oscillations in sentences condition and sentence repetition performance indicates that a person with a more decreased delta-band oscillation in the sentences condition of word list recall is likely to show a higher accuracy of sentence repetition. The result is not perfectly aligned but relevant to the previous studies that shed light on the association between the desynchronization of neural oscillations and sentence processing (Hanslmayr et al., 2012; Lum et al., 2022; Meltzer & Braun, 2011; Vassileiou et al., 2018).

Hanslmayr et al. (2012) proposed the information via desynchronization hypothesis in their review paper and argued that desynchronization, the decrease in the alpha and beta band, can be helpful for memory encoding and retrieval. Meltzer and Braun (2011) also observed a decrease in the alpha/beta band (8 – 30 Hz) in general, but with more decrease in cognitively more demanding sentences (reversible sentences and object-relative sentences) than the less demanding sentences (non-reversible sentences and subject-relative sentences). These results indicate that a greater desynchronization of the power in neural oscillations can be found during the processing of sentences that are more complex and cognitively demanding, and the successful desynchronization of neural oscillations during the encoding of sentences can be beneficial for memory retrieval.

However, unlike the hypothesis of the present study, there was no significant association between the beta-band oscillations and sentence repetition. While there was no significant association, the beta band also showed a negative correlation with sentence repetition, similar to the delta band. Since the sentences and word lists used in the present study were not semantically and prosodically natural, it is possible that the power differences in the beta band are diminished as a result. Also, note that the sentences used in word list recall followed syntactic structures yet were not fully grammatical. Lastly, it is also possible that the delta-band oscillations are more important than the beta band in SSE in sentence repetition (Bonhage et al., 2017; Ding et al., 2016; Keitel et al., 2018; Lu et al., 2022). Further research is needed to verify the findings of the current study.

Clinical implications

SSE in understanding sentence repetition of individuals with DLD

From the scope of my knowledge, the present study is the first attempt to investigate SSE to understand the on-line morphosyntactic processing in sentence repetition. Also, while the present study involved monolingual adults without language disorders, this is the first study that sheds light on SSE as a hidden factor that individuals with DLD may show a reduced effect in their sentence repetition. As stated in the introduction, it is difficult to examine morphosyntactic processing in sentence repetition apart from the differences in morphosyntactic knowledge. Focusing on SSE in sentence repetition by controlling the effect of lexical-semantics and the number of words may allow future studies to explore on-line language processing in individuals with DLD.

Based on the present findings, it is important for future studies to establish whether the difficulty in on-line morphosyntactic processing is a significant factor in the limited sentence repetition of individuals with DLD. This is because the intervention strategies for individuals with DLD may vary according to these future findings. For example, if the difficulty in on-line morphosyntactic processing is a significant factor, individuals with DLD will show a diminished gap between sentences and word lists in WLR compared to TD. As described in the introduction, the gap between sentences and word lists indicates the benefit of having syntactic structures when memorizing lexical items. The reduced SSE, therefore, can be interpreted as the result of ineffective top-down morphosyntactic processing in recalling words in sentences in individuals with DLD. Thus, the intervention targeting on-line morphosyntactic processing will be effective in improving sentence repetition performance in individuals with DLD.

In contrast, if the difficulty in on-line morphosyntactic processing is not a significant factor, individuals with DLD will show a similar gap between sentences and word lists in WLR as their TD peers. In this case, clinicians may assume that their morphosyntactic processing is relatively preserved, at least when the lexical-semantic and morphosyntactic knowledge is well-acquired. In this scenario, separating morphosyntactic processing from morphosyntactic information in sentence repetition is not essential, and if clinicians observe preserved morphosyntactic knowledge, they can anticipate that morphosyntactic processing will be preserved as well. Therefore, intervention approaches focusing solely on morphosyntactic processing may not be necessary for enhancing sentence repetition performance in individuals with DLD.

Neural oscillations in understanding sentence repetition of individuals with DLD

Also, bringing EEG and brain oscillations into the understanding of the underlying processes of sentence repetition is another clinical implication of the present study. Although various studies on SSE employed EEG and brain oscillations (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Bonhage et al., 2017; Lam et al., 2016), no previous studies have been conducted to verify the role of SSE in sentence repetition. Examining neural oscillations using EEG allows us to observe the internal processing patterns that cannot be detected by behavioral measures. For example, the current study found the timing of SSE was mainly found in the final two words of the presentation by the non-parametric cluster-based permutation statistics. It is also helpful to use an electrophysiological measure to investigate internal processing that is not shown in the behavioral measures due to the compensatory mechanisms used by individuals with DLD to overcome language processing deficits (Haebig et al., 2017).

Background noise in understanding sentence repetition of individuals with DLD

The present study is also the first examination of the relationship between SSE and noise in the context of sentence repetition. It is important for both theoretical and ecological validity reasons to investigate how SSE can vary depending on the presence of speech sound degradation. It is also very important to include background noise, especially for future studies targeting bilingual populations. For example, the Ease of Language Understanding model (ELU) (Rönnberg et al., 2008, 2013) addressed the difficulties in speech perception in noise of bilingual

L2 speakers compared to monolinguals. The ELU assumes that while listeners listen to speech streams, the sublexical information is temporarily stored in RAMBPHO (rapid, automatic, multimodally bound phonological representations). If the information in RAMBPHO matches the long-term phonological representations in individuals' long-term memory, the information is processed implicitly with the support of long-term memory. However, if there is a mismatch between the sublexical information in RAMBPHO and the long-term phonological information due to a degraded acoustic signal or unfamiliar speakers or accents, explicit processing involving working memory is required to resolve the mismatch. Therefore, it would be challenging for non-fluent L2 speakers to process sentence repetition in noise because the mismatch can increase their working memory demands.

Similar to bilingual populations, individuals with DLD may also present greater difficulties in sentence repetition in noise. While the findings of the current study did not show the effect of noise or the interaction between SSE and noise in neural oscillations, it is plausible that individuals with DLD may show the main effect of noise and its interaction with SSE in sentence repetition.

The study will also provide a foundational understanding of how SSE in noise is processed by monolingual adults without language impairments. On the basis of the current findings, it is possible to carry out additional research comparing SSE in sentence repetition among children and adults, monolinguals and bilinguals, and individuals with and without DLD. For instance, the present study found a significant association between delta-band oscillations and sentence repetition. Other populations may exhibit a different frequency band of neural oscillations associated with sentence repetition performance depending on their cognitive-linguistic processing patterns when remembering and recalling sentences.

Limitations and future directions

First, because the current study involved a within-group design without between-group factors, there is a limitation in hypothesizing the results of future studies involving different populations. For instance, the present study did not compare the results between children and adults, nor between individuals with and without DLD; therefore, it is still unknown how the differences in SSE can interact with group differences. Therefore, future studies comparing different groups would be necessary to understand how SSE can vary depending on the cognitive-linguistic profiles of individuals.

Also, studies involving different types of noise or levels of intensity of noise would be needed to fully understand how bottom-up disturbances play a role in SSE of sentence repetition. Although the current study used energetic masking involving white noise, information masking instead of white noise may be more effective. Information masking can minimize the evoked potential driven by the physical appearance of acoustic noise and consequently would allow us to observe more about *internal synchronicity* than *entrainment proper*. Also, as mentioned, the intensity of noise used in the current study (+ 4 dB SNR) may not be enough to cause power differences in neural oscillations. Therefore, further studies involving either a greater intensity of background noise or various noises with different intensity levels would be essential to understanding the genuine role of noise in SSE in sentence repetition.

While the present study controlled the effects of lexical-semantics by utilizing the closed set of words, it was not possible to control the sentence-level semantics. Although the sentences and word lists conditions were comprised of an identical set of words, the words in the sentences condition were semantically more plausible because the transition of the words in the sentences condition makes more sense and is more familiar than in the word lists condition. To comprehend the significance of the morphosyntactic processing in sentence repetition, it will be necessary for future research to distinguish between sentence-level semantics and SSE in neural oscillations.

Lastly, future research utilizing natural sentences in continuous speech is required to confirm whether the current findings are consistent when actual sentences are involved. The experimental stimuli and presentation adopted in the present study were not natural in order to control the effects of intonation and lexical-semantic information between sentences and word lists. To validate that the results of SSE in the current study reflect sentence processing in real life, observing the effect using natural sentences is essential. Recent electrophysiological studies have already shown the feasibility of using continuous speech in naturalistic environments (Alday, 2019). Therefore, it is technically possible for future studies to investigate the SSE in the current study using natural sentences. Additionally, due to the presence of word lists condition, participants might treat the WLR task as a verbal memory task rather than a sentence-level one; therefore, the results may be more indicative of working memory than morphosyntactic processing. The positive correlation between sentence repetition and the behavioral accuracy of the WLR sentences condition was significant, implying that the participants may perform the WLR similarly to sentence repetition. Future studies incorporating continuous speech will confirm the relationship between the SSE and the on-line morphosyntactic processing in the present study.

Conclusion

This study examined SSE in sentence repetition in monolingual adults with typical language development using EEG. SSE was found in the beta (13 – 30 Hz) and delta (1 – 4 Hz) bands of neural oscillations. SSE in monolingual adults with typical language development is relevant to the beta and delta-band neural oscillations, particularly when the number of words exceeds the short-term memory limit of 4 ± 1 chunks. Behavioral and neurophysiological evidence demonstrates that SSE substantially enhances short-term memory capacity through the use of sentence structures. Therefore, the lack of SSE would significantly reduce sentence repetition performance. For a comprehensive understanding of the importance of sentence repetition in assessing individuals with DLD, it is necessary to examine SSE in populations with various cognitive-linguistic profiles, including DLD.

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Appendix A

Word List Recall

The items below will be presented twice to form noisy and clear speech sound conditions. The first ten items (the first block in a bold box in each table) in both sentences and word lists conditions will be used in the behavioral version as well as the EEG version of the task.

A. Sentences

adj	agent N	aux	verb	object N	conj	verb	Object N
big	friend	is	washing	coat	and	making	juice
black	frog	is	loving	school	and	walking	park
gentle	cat	is	finding	cup	and	giving	cheese
good	bear	is	biting	cookie	and	putting	hat
happy	fish	is	helping	dog	and	sitting	chair
little	baby	is	opening	bottle	and	throwing	ball
old	boy	is	eating	apple	and	seeing	hand
pretty	duck	is	reading	book	and	hugging	pig
slow	girl	is	drinking	milk	and	kicking	tree
white	lion	is	looking	bird	and	having	shoe
tired	uncle	is	dropping	jacket	and	covering	grass
thirsty	child	is	touching	nose	and	waiting	flower
quiet	police	is	holding	stone	and	building	kitchen
new	doctor	is	catching	star	and	drying	sweater
nice	teacher	is	drawing	moon	and	showing	table
clean	daddy	is	bringing	snow	and	buying	belt
fast	mommy	is	carrying	water	and	fixing	room
cute	brother	is	hiding	stick	and	shaking	head
sleepy	sister	is	taking	balloon	and	listening	rain
hungry	nurse	is	painting	garage	and	thinking	window
silly	snowman	is	breaking	glass	and	dragging	couch
young	cowboy	is	sharing	bicycle	and	searching	bread
dirty	mouse	is	writing	name	and	boiling	egg
polite	cousin	is	pushing	train	and	frying	potato
giant	turtle	is	driving	car	and	tickling	face
kind	grandma	is	sliding	hill	and	dumping	trash

colorful	clown	is	spilling	coffee	and	swinging	arm
shiny	horse	is	jumping	rope	and	wiping	dish
scary	penguin	is	brushing	teeth	and	closing	door
long	snake	is	watching	tv	and	tasting	lemon

B. Word lists

verb	verb	agent N	object N	aux	object N	adj	conj
making	washing	friend	juice	is	coat	big	and
walking	loving	frog	park	is	school	black	and
giving	finding	cat	cheese	is	cup	gentle	and
putting	biting	bear	hat	is	cookie	good	and
sitting	helping	fish	chair	is	dog	happy	and
throwing	opening	baby	ball	is	bottle	little	and
seeing	eating	boy	hand	is	apple	old	and
hugging	reading	duck	pig	is	book	pretty	and
kicking	drinking	girl	tree	is	milk	slow	and
having	looking	lion	shoe	is	bird	white	and
covering	dropping	uncle	grass	is	jacket	tired	and
waiting	touching	child	flower	is	nose	thirsty	and
building	holding	police	kitchen	is	stone	quiet	and
drying	catching	doctor	sweater	is	star	new	and
showing	drawing	teacher	table	is	moon	nice	and
buying	bringing	daddy	belt	is	snow	clean	and
fixing	carrying	mommy	room	is	water	fast	and
shaking	hiding	brother	head	is	stick	cute	and
listening	taking	sister	rain	is	balloon	sleepy	and
thinking	painting	nurse	window	is	garage	hungry	and
dragging	breaking	snowman	couch	is	glass	silly	and
searching	sharing	cowboy	bread	is	bicycle	young	and
boiling	writing	mouse	egg	is	name	dirty	and
frying	pushing	cousin	potato	is	train	polite	and
tickling	driving	turtle	face	is	car	giant	and
dumping	sliding	grandma	trash	is	hill	kind	and
swinging	spilling	clown	arm	is	coffee	colorful	and
wiping	jumping	horse	dish	is	rope	shiny	and
closing	brushing	penguin	door	is	teeth	scary	and
tasting	watching	snake	lemon	is	tv	long	and

Appendix B

Sentence Repetition Task Stimuli

[Argument]

The worker carved the wood with his knife but denied the evidence.
The widow painted the shed and frightened the mice with her hammer.
The president urged the army to act and blocked their glory.
The observer located the park and taught the kids the method.
The soprano played the passage and read the joke to the public.
The insider assigned the woman the verse to check her vision.
Our grandmother injured her ego yet knit our mother new linen.
My brother studied the item then filled the bowl with liquid.
This generation tempted hope and grasped success with both hands.
The scholar ate an orange and inserted the seeds in sand.
The principal saddened the child but coaxed him into class.
The hotshot baked her assistant a cake and added a cherry.

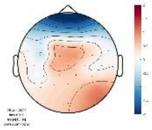
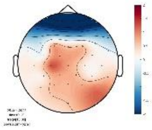
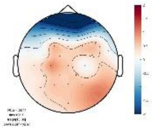
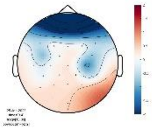
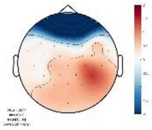
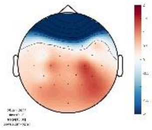
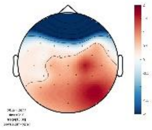
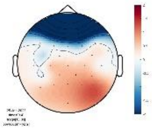
[Adjunct]

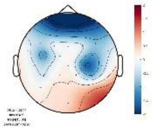
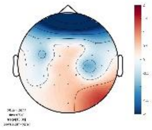
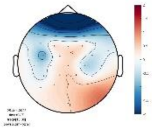
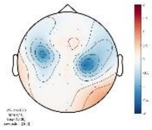
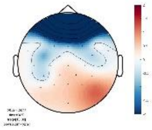
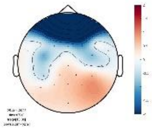
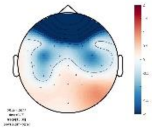
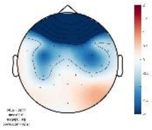
The genius realized the date at dawn and wrote in the cold.
My patient protested in the bath and dripped down the long hall.
The soul visited before the judgment but prayed at great length.
People hurried at the accident but crumbled at the main square.
The author cheated the agency at first and bragged in public.
The dog struggled in the pet motel and jumped at the signal.
The staff tired before the farewell and complained in the cellar.
The driver rushed for the jokester but crashed on the dreaded curve.
Our guide worried at the emergency but decided later.
The specialist froze at the call then replied in confusion.
The competition melted at our strength but rose after the snub.
The corporal flew at noon over the sound and drove in terror.

Appendix C

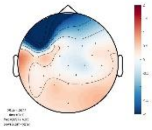
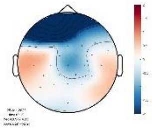
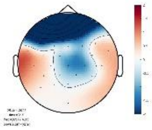
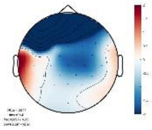
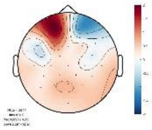
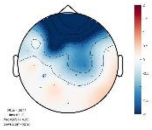
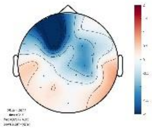
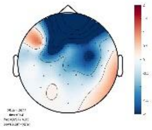
Topographic Changes Over Time

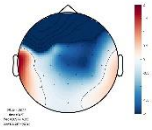
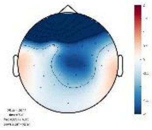
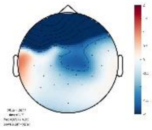
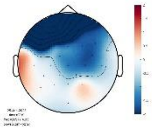
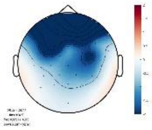
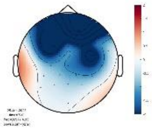
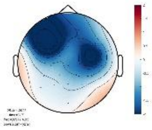
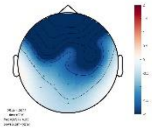
A. Beta band

Time	**0 – 1 sec**	**1 – 2 sec**	**2 – 3 sec**	**3 – 4 sec**
Example (sentences)	*big*	*friend*	*is*	*washing*
Scalp map (sentences)				
Example (word lists)	*making*	*washing*	*friend*	*juice*
Scalp map (word lists)				

Time	**4 – 5 sec**	**5 – 6 sec**	**6 – 7 sec**	**7 – 8 sec**
Example (sentences)	*coat*	*and*	*making*	*juice*
Scalp map (sentences)				
Example (word lists)	*is*	*coat*	*big*	*and*
Scalp map (word lists)				

B. Delta band

Time	**0 – 1 sec**	**1 – 2 sec**	**2 – 3 sec**	**3 – 4 sec**
Example (sentences)	*big*	*friend*	*is*	*washing*
Scalp map (sentences)				
Example (word lists)	*making*	*washing*	*friend*	*juice*
Scalp map (word lists)				

Time	**4 – 5 sec**	**5 – 6 sec**	**6 – 7 sec**	**7 – 8 sec**
Example (sentences)	*coat*	*and*	*making*	*juice*
Scalp map (sentences)				
Example (word lists)	*is*	*coat*	*big*	*and*
Scalp map (word lists)				

VITA

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Education

Doctor of Philosophy in Communication Sciences and Disorder and Language Science **2023**
The Pennsylvania State University, University Park, PA, USA

Master of Arts in Communication Disorders **2017**
Ewha Womans University, Seoul, Republic of Korea

Bachelor of Arts in English and Counseling Psychology **2013**
Handong Global University, Pohang, Republic of Korea

Selected Publications and Presentations

Sandberg, C. W., Exton, E., Coburn, K., **Chun, S**., & Miller, C. (2022). Event related potential exploration of the organizational structure of abstract versus concrete words in neurologically intact younger adults. *Brain and Language, 230*.

Chun, S., & Lee, J. (2022, June). *The role of language processing in the speaking rate of English-monolingual and bilingual adult speakers.* Poster session presented at the International Workshop on Language Production (IWoLP), Pittsburgh, PA, USA.

Chun, S., & Miller, C. (2022, June). *Electrophysiological patterns of sentence superiority effect in sentence repetition.* Poster session presented at the International Max Planck Research School (IMPRS) Conference, Nijmegen, Gelderland, Netherlands.

Chun, S., & Miller, C. (2021, November). *Bottom-up & top-down processing of sentence repetition in Spanish-English bilinguals.* Poster session presented at the Annual ASHA Convention. Washington DC & virtual, USA.

Chun, S., & Miller, C. (2021, June). *The underlying subcomponents of sentence repetition in assessing children with developmental language disorders*. Poster session presented at Symposium on Research in Child Language Disorders (SRCLD), Madison, WI, USA. (virtual)

Sandberg, C. W., Exton, E., Coburn, K., **Chun, S.**, & Miller, C. (2020, October). *Event related potential and time frequency exploration of the organizational structure of abstract versus concrete words in neurologically intact younger adults* [Sandbox poster presentation]. Society for the Neurobiology of Language.

Selected Awards/Honors

University Graduate Fellowship, The Pennsylvania State University (2019-2021)