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THE SYNTACTIC STRUCTURE AND DISTANCE EFFECT ON SENTENCE PROCESSING IN TURKISH

Türkçede Tümce İşlemlemede Sözdizimsel Yapı ve Uzaklık Etkisi

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Abstract: Previous research using the Visual World Paradigm (VWP) has shown that sentence processing is influenced by the visual environment in which sentences are presented. This study investigates online processing of syntactic complexity and linear distance in Turkish sentence processing through an eye-tracking experiment using the VWP. We examined how auditory-visual information interacts with syntactic complexity (nested vs. linear) and sentence distance (short vs. long). We hypothesized that auditory-visual information is sensitive to online processing of syntactic complexity in subject-relative clauses (SRCs), and the linear distance between pre- and postverbal positions is critical for incremental processing. Our findings showed that syntactic complexity affected gaze duration, whereas linear distance had a distinct effect.

Key words: *Syntactic complexity, Linear distance, Visual world paradigm, Eye movements, Turkish*

Öz: Önceki araştırmalar, Görsel Dünya Paradigması'nı (GDP) kullanarak, tümce işlemlemenin, tümcelerin sunulduğu görsel ortamdan etkilendiğini

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göstermektedir. Bu çalışma, GDP kullanılan bir göz izleme deneyi aracılığıyla Türkçede tümce işlemlemede sözdizimsel karmaşıklığın ve çizgisel uzaklığın süreç-içi işlenmesini araştırmaktadır. İşitsel-görsel bilginin sözdizimsel karmaşıklık (içe-gömülü ve çizgisel) ve tümce uzaklığı (kısa ve uzun) ile nasıl etkileşime girdiği incelenmiştir. Çalışmada işitsel-görsel bilginin, özne ilgi tümceciklerinde sözdizimsel karmaşıklığın süreç-içi işlemlemesine duyarlı olduğu ve eylem-öncesi ile eylem-sonrası arasındaki çizgisel uzaklığın artımlı işlemleme açısından önemli olduğu varsayımlanmıştır. Bulgularımız, sözdizimsel karmaşıklığın bakış sürelerini etkilediğini ve çizgisel uzaklığın belirgin bir etkisinin bulunduğunu göstermiştir.

Anahtar sözcükler: *Sözdizimsel karmaşıklık, Çizgisel uzaklık, Görsel dünya paradigması, Göz hareketleri, Türkçe*

1. INTRODUCTION

The online effects of syntactic structure and distance on sentence processing have been widely discussed (Altmann & Kamide, 2007; Makuuchi et al., 2009; Romero et al., 2010; Ivanova & Ferreira, 2018; Delage, Stanford, & Durrleman, 2021; Cheng, 2023) using various approaches. While there is a large number of impacts on syntactic structure in Turkish (Kırkıcı, 2004; Özçelik, 2006; Aydın, 2007; Dinçtopal-Deniz, 2010; Turan, 2018, 2020; Akal, 2021; Uzunca & Akal, 2023), there is a relatively limited amount of research (Kaya, 2012; Çalışkanel, 2013) investigating the incremental and auditory-visual information in sentence processing. Theoretical approaches to syntactic distance include two different types: structural distance (Hawkins, 1999, 2004; O'Grady, Lee, & Choo, 2003) and linear distance (Tarallo & Myhill, 1983; Gibson, 1998; Babyonyshev & Gibson, 1999). While linear distance is defined as the number of units between fillers and gaps within a sentence, structural distance emphasizes branching and filler-gap properties (Hsu & Chen, 2013; Pozniak, Huang, & Hemforth, 2016).

The approaches cited above have been discussed under two different hypotheses: the Linear Distance Hypothesis (LDH) (Hawkins, 1999) and the Structural Distance Hypothesis (SDH) (Collins, 1994; O'Grady, 1997, 1999; Hawkins, 1999, 2004). According to the LDH, there is a linear distance between the head and gap, and notably, the greater the number of units between these structures, the greater the processing capacity. Processing speed also increases simultaneously and

proportionally. The SDH, conversely, is concerned with the effect of structure on syntactic hierarchy. The distance between units and fillers is related to the branching in the sentence structure. Thus, as the number of nodes in the syntactic tree increases in size and syntactic complexity, so does the processing load. In contrast to linear distance, the effect of structural distance is specifically related to the truncation process in the syntactic tree. The processing load of structural distance is independent of working memory (WM), consistent with previous theories (Newmeyer, 1992; Chomsky, 2013). Although this processing variation is acknowledged as a primary focus in cognition and in universal grammar, it is considered a fundamental feature of language. It has been suggested that the larger the distance between elements in a sentence, the more difficult the process of constructing sentence structure becomes (Chomsky, 2013, 2016). Sentences with longer structural distances are more difficult to comprehend than those with shorter structural distances.

In the current study, we predict that syntactic complexity (nested vs. linear) will result in longer dwell times for nested sentences than for linear sentences, due to the greater syntactic complexity of nested sentences. We expect that when the syntactic elements representing the target item are located preverbally, participants' average gaze duration will be higher in long sentences compared to short sentences. Additionally, we expect that, in nested sentences, the combination of long structural distance and preverbal position results in the longest gaze durations. In contrast, in linear sentences, the postverbal position indicates a shorter processing time. In the light of the above, we hypothesised that (i) auditory-visual information is sensitive to online sentence processing of syntactic complexity in the subject-relative clauses (SRCs), (ii) the linear distance between preverbal and postverbal positions in Turkish is critical for incremental processing between long and short sentences, and (iii) syntactic information and WM may share separate cognitive representations during online sentence processing. Before presenting our results from an online Visual World Paradigm (VWP) experiment, we will first discuss the theoretical assumptions and findings regarding syntactic structure and distance processes in auditory-visual language comprehension.

1.1. THE EFFECT OF SYNTACTIC COMPLEXITY

LDH and SDH are often explained in terms of RCs to demonstrate differences in processing load (e.g., King & Just, 1991; Gibson, Hickok, & Schütze, 1994; Caplan & Waters, 2002). These hypotheses suggest that SRCs are processed faster than object relative clauses (ORCs). While this distinction is important in online and offline syntactic processing studies, the current research focuses explicitly on SRCs because they are relevant to syntactic complexity manipulations in Turkish. Unlike the previous studies that compare SRCs and ORCs, the present study directly investigates the SRCs to examine the processing difficulty of nested structures. Previous work also suggests that processing ORCs requires greater working memory capacity than processing SRCs (Kaan, 1997; Gibson, 1998, 2000). In head-first languages like English, where the head is located at the front, the gap occurs after the filler. In Turkish, subject-relative sentences are typically constructed with the suffix {-(y)An}[4] (i.e., [t_i *adam-a koş-an çocuk*$_i$ *yere düştü*] [t_i *the child who ran to the man*$_i$ *fell to the ground*]). Object-relative clauses are typically formed by adding the {-DIK} suffix. For instance, in the sentence [*adam-ın* t_i *çarp-tı-ğ-ı çocuk*$_i$ *yere düştü*] [*the child* t_i *who the man*$_i$ *hit fell to the ground*], the {-DIK} suffix is used to form the object-relative clause (for more information, see Underhill, 1972; Hankamer & Knecht, 1976; Kahraman, Sato & Sakai, 2010; Özge, Marinis & Zeyrek, 2015; Kahraman & Hirose, 2018; Bulut et al., 2019).

In one study (Kırkıcı, 2004), syntactic ambiguity in RCs is strongly influenced by the change in lexical-semantic information. In line with this, subject-object asymmetry has a greater impact when the object follows the verb, making the structure more difficult to comprehend (Kahraman, Sato, & Sakai, 2010). On the other hand, Aydın and Zagvozdkina (2019) compared early and late processing stages of structural distance in Turkish sentences. In the context of incremental processing, ORCs are processed after filler-gap dependencies and have a significant impact on RCs. Their findings are consistent with the results of a self-paced listening study (Özge et al., 2015). They investigated the structural differences in morphosyntactic processing between Turkish adults and children aged 5-8 years. Their overall results showed that morphosyntax significantly affected the distance for both groups. A recent study (Logačev et al., 2022) investigated

[4] RCs in Turkish are derived from Turkish morphemes such as {-(y)An} for SRCs and {-DIK} for ORCs.

how syntactic complexity affects syntactic ambiguity in RCs in an online reading experiment with the (un)ambiguous conjunctions. They argued that there was no difference between syntactic ambiguity and structural distance in Turkish RCs. So far, little attention has been paid to investigating how syntactic complexity and distance might influence online auditory-visual sentence processing in Turkish SRCs, with integration with WM.

The capacity theory of comprehension (i.e., the single-resource model) (Just & Carpenter, 1992) suggests a unitary WM system for language comprehension. Participants' performance on the reading span task, in relation to syntactic complexity, supports an interactive, single-resource model. A well-known study (King & Just, 1991) compared participants' reading performance between ORCs and SRCs using a self-paced sentence comprehension task. Their results were consistent with those of Just and Carpenter (1992), who used eye-tracking measures of RCs. They found that low-ability readers had more difficulty processing ORCs than high-ability readers; however, the difference was not significant, and there was no interaction with WM resources for reading performance on SRCs between low- and high-ability readers. In the current study, we aimed to investigate the role of linear distance and syntactic complexity in online sentence processing from a cognitive perspective.

1.2. THE EFFECT OF STRUCTURAL DISTANCE

Structural distance typically refers to the hierarchical relationships among elements within a sentence. In the current study, we distinguish between structural distance, which refers to syntactic branching within a sentence, and linear distance, which is based on word order and the number of intervening elements between syntactic units. Long- or short-distance dependencies are associated with two different linguistic units separated by one level of distance in a linear sequence. This so-called dependency is the filler-gap dependency (Hawkins, 1994), which directly utilizes syntactic movement or RC attachment strategies. The filler-gap dependency means that when a filler moves away from its primary position, it leaves a gap. The head, considered the fundamental element of the sentence (Abney, 1989), primarily influences syntactic organization. The position of the head in the structure can either reduce or increase the online processing load. For example, differences in online processing may be due to the position of the head in languages such as German (Bader & Lasser, 1994),

which uses verb-final structures, and Japanese (Miyamoto & Takahashi, 2002), which uses object-verb order. For instance, Turkish follows a Subject-Object-Verb (SOV) sequence, whereas English follows a Subject-Verb-Object (SVO) sequence. Word orders can scramble at many positions, including preverbal, immediately preverbal, or postverbal. Turkish word-order is relatively more flexible in preverbal and postverbal positions. Various linguistic elements, primarily syntactic, semantic, morphological, prosodic, and pragmatic factors, influence this flexibility (e.g., Erguvanlı, 1984; Kural, 1992; Göksel, 1998; Kornfilt, 2003; İşsever, 2007).

Studies on the comprehension effects of word-order differences in preverbal and postverbal positions in Turkish (e.g., Aydın & Cedden, 2010) have generally focused on integration costs in structures involving filler-gap constructions, which require syntactic movement. Once the filler has been determined, participants immediately assign it to a relevant gap position, following the Active Filler Strategy. For instance, in languages like Turkish, this process is typically sequential, beginning from the left and moving towards the right, which is appropriate to the processing structure of the relevant language. Then it relates these sentence units to specific gap positions that require additional syntactic information. In contrast, Ng (2008) proposes that this scenario operates in the opposite direction. Participants first identify the gap and then determine the position of the filler in a sentence analysis.

Online sentence processing in memory-based accounts is known to be limited by the participants' WM capacity. Dependency locality theory, which is related to memory-based accounts (Gibson, 1998, 2000), explains the filler-gap strategy as a function of the linear distance between the head and the gap. In the current study, however, manipulating linear distance mainly focuses on the number of syntactic elements between the subject and the verb in long and short sentences, while the syntactic structure remains constant. This allows us to examine the specific effects of linear distance on sentence processing, independent of syntactic complexity.

Many studies examined on the separate and/or interactive cognitive resources on WM in Turkish (Kaya, 2012; Çalışkanel, 2013; Arslan, Hohenberger & Verbrugge, 2017; Yücel, 2022) and many other languages, such as English (Fedorenko, Gibson, & Rohde, 2006; Romero et al., 2010; Weighall & Altmann, 2011), German (Fiebach, Schlesewsky, & Friederici, 2001; Fiebach et al., 2005; Makuuchi et

al., 2009; Vos et al., 2010), French (Stanford, Durleman, & Delage, 2019; Delage & Frauenfelder, 2020; Delage et al., 2021), Japanese (Nakatani & Gibson, 2009), Korean (Kwon, 2008), Italian (Domenico & Mattea, 2009), Spanish (Vos et al., 2018), Dutch (Kolk et al., 2003; Swet et al., 2007), Arabic (Cohen-Mimran, Adwan-Mansour, & Sapir, 2012), Mandarin Chinese (Chen et al., 2008; Cheng, 2023), and Hindi (Vasishth et al., 2011). These studies indicate the significant role of WM in syntactic processing. However, while these studies generally focus on the interaction between syntactic structure and WM, the current study focuses on the association between linear distance and syntactic complexity, mainly how these two elements interact in online sentence processing in Turkish.

Syntactic differences at phrasal and branching levels are directly relevant to cognitive processing of both simple and complex RC structures (Vasishth et al., 2011; Myachykov et al., 2013; Ivanova & Ferreira, 2018). Prior research in Turkish has investigated the interaction between participants' WM and syntactic processing, mainly focusing on complexity and distance effects, using distinct methodologies. In line with this, studies on RCs attachment (Kaya, 2012), the effects of gender and age (Çalışkanel, 2013), recursion (Arslan et al., 2017), and the integration of listening and speaking in a second language (Yücel, 2022) have reported strong associations between sentence comprehension and WM load.

There is an opposing view of the integration between structure and WM load during online sentence comprehension at the psycholinguistic and/or neurolinguistic level (Caplan & Waters, 1999; Fiebach et al., 2005; Fedorenko et al., 2006; Traxler & Tooley, 2007; Makuuchi et al., 2009; Romero et al., 2010; Cheng, 2023). Fiebach et al. (2005) investigated local parsing processes and WM interaction in German wh-questions following the non-syntactic WM approach. Results imply that WM and syntactic processing should be treated as separate systems. Fedorenko et al. (2006) then conducted two experiments using dual-task and spatial-task paradigms. In their first experiment, they found an interaction between arithmetic and syntactic complexity as an overlapping factor on WM, while a separate WM system was proposed for a separate memory load between sentence comprehension and verbal information, to the extent that their results for interactive WM storage resources are inconsistent with previous findings suggesting a segregated WM load for verbal information (see Caplan & Waters, 1999). A well-known study for the

segregated WM approach by Makuuchi et al. (2009) investigated spatial processing using fMRI. They analyzed the syntactic complexity (single/double nested vs. linear) and distance (long vs. short) effects of RCs in German sentences within a computational faculty of human language using the resources of WM load. Their results suggested a separate cognitive interpretive resource for WM called a non-syntactic level of sentence comprehension. Romero et al. (2010) also found separate processing of syntax and WM in English. A relatively recent study (Cheng, 2023) supported the cross-linguistic findings of Makuuchi et al. and Romero et al. Cheng reported similar findings for Mandarin Chinese. Interference tasks provided independent processing of WM (digit/lexical recall) and syntactic complexity. Overall, these studies suggest that WM and syntactic processing may operate through different but interacting language mechanisms. The current study contributes cross-linguistic evidence from an agglutinative, head-final language by investigating whether Turkish SRCs exhibit similar or distinct findings to those of this interaction between WM and syntactic processing.

2. THE CURRENT STUDY

The current study aims to investigate online processing of auditory-visual linguistic information, specifically examining the effects of linear distance and syntactic complexity on sentence comprehension by manipulating preverbal and postverbal positions in Turkish. Online sentence comprehension in languages such as Turkish, which has a flexible and free word-order, follows a left-to-right, sequential processing strategy (e.g., Erguvanlı, 1984; Kural, 1992; Phillips, 2003). Previous work has shown a lower information load in postverbal than in preverbal positions in Turkish (e.g., Erguvanlı, 1984; Kural, 1992). This relates to left-to-right processing, which increases the cognitive load. Studies suggest that postverbal elements generally reflect background and/or tail information (Gibson, 1998; Kural, 1992), which is not directly related to a new sentence focus.

By manipulating linear distance and syntactic complexity in Turkish SRCs, the current study investigates their interactions with WM. We hypothesize that moving the target item from preverbal to postverbal position would not necessarily increase cognitive load on participants' WM capacities, as previous work might suggest for other syntactic structures. This mismatch may stem from the particular syntactic

violation presented in the current study, which characterized a single nested structure in SRCs.

The current study tests three hypotheses using the VWP and eye-tracking methods. We operationalized looking behavior as a function of dwell time percentage and accordingly defined dwell time percentage as the primary dependent variable reflecting syntactic processing. Dwell percentage refers to the total time participants fixated on a particular region of interest (the target or competitor image on the 2x2 grid) during the auditory sentence presentation.

First, we predict that syntactic complexity will influence incremental processing in Turkish and that this influence will differ between long and short sentences. Long and short sentences in the present study indicate the linear distance between the target item and the other syntactic elements, such as the subject or object. Long sentences have greater distance; short sentences are closer. This aspect of structural distance is distinct from syntactic complexity, which is analyzed in terms of nested vs. linear structures. Therefore, the current study considers syntactic complexity and linear distance as separate variables. Studies on syntactic complexity, which mark subject-object asymmetry (see Gibson, 1998; Nakano et al., 2002; Miyamoto & Takahashi, 2002, 2004), have shown that ORCs are more difficult to process than SRCs. To evaluate the online processing of syntactic complexity in Turkish, our study uses preverbal clauses formed with a single nested SRC structure, marked by the suffix {-(y)An}.

The second hypothesis concerned the processing of short versus long sentences. We predict that sentence length (short vs. long) will affect the online processing of the target item, as reflected in the dwell time percentage. Previous work has demonstrated that Turkish exhibits a flexible word order, allowing syntactic units to appear in both pre- and postverbal positions (Erguvanlı, 1984; Kural, 1992). The tail of the information is postverbal, usually without new focus (Erguvanlı, 1984; Kılıçaslan, 1994; Göksel, 1998; İşsever, 2003).

The final hypothesis examines the interaction between linguistic information and WM during online sentence comprehension with syntactic complexity and distance manipulation. Specifically, we hypothesize that these two cognitive processes may either overlap or operate independently. Previous studies have taken two opposing approaches to understand better the role of WM in processing the dependency between syntactic complexity and linear distance. Two distinct mechanisms for the interactions are proposed by studies on

non-syntactic (Just & Carpenter, 1992; Kumcu & Thompson, 2020) and syntactic (Fiebach et al., 2005; Makuuchi et al., 2009; Romero et al., 2010; Cheng, 2023) violations. WM processing and sentence comprehension share a common mechanism, utilizing the same cognitive resources (Santi & Grodzinsky, 2007; Wendt, Brand, & Kollmeier, 2014). In accordance with this approach, syntactic processing and WM are separate cognitive representations (Knoeferle & Crocker, 2007; Makuuchi et al., 2009; Romero et al., 2010; Cheng, 2023). Consistent with previous findings, we expect syntactic processing to consist of separate WM resources for syntactic complexity and linear distance.

3. METHODS

3.1. PARTICIPANTS

57 native Turkish-speaking monolinguals were recruited for the study. Two participants were excluded from the experiment due to poor data quality during the eye-tracking procedure. Thus, analyses were conducted with 55 participants (22 males; M_{age} = 24.11, SD = 5, range 18–39). All participants reported normal vision, no hearing/speech difficulties, and no neurological disorders. All participants were informed of the procedure details and provided written consent in Turkish. Debriefing confirmed participants were naive to the aims. The study was conducted at the Linguistics Laboratory of Ankara University. All procedures performed in this study were approved by the Ethics Committee of Ankara University (approval number: 02/06, approval date: 17 February 2022).

3.2. MATERIALS

The VWP experiment consisted of four conditions, arranged in a 2×2 design with the factors STRUCTURE (nested vs. linear) and DISTANCE (long vs. short). There were 240 sentences (40×4 = 160 experimental conditions + 40×2 = 80 fillers) and 480 black and white drawings. All sentences were manipulated to vary in syntactic complexity and preverbal/postverbal distance. 80 sentences were included as fillers to balance the number of 40 sentences for each experimental condition.

The STRUCTURE condition was developed by manipulating the syntactic properties of nested and linear structures. Accordingly, nested structures were derived from SDH (see conditions A and B),

and linear structures were manipulated according to LDH (see conditions C and D). Conditions A and B had a syntactically nested form, where a single nested construction was present in SRCs, whereas conditions C and D represented linear structures without embedding. On the other hand, the DISTANCE condition was determined by the number of elements between the main subject and the verb in the clause. Specifically, conditions A and C had long-distance configurations, with eight words separating the main subject and the verb. In contrast, conditions B and D featured short-distance configurations, with only five words between. Furthermore, the target item (*kediyi*) appeared in preverbal positions in the conditions A and C. In contrast, it was located in postverbal positions in conditions B and D. The main subjects and objects of the clauses were consistently placed in the same syntactic positions as in the first and sixth positions (see Table 1). Filler sentences varied in terms of target positioning and distance, as illustrated in sample sentences for preverbal positions (e.g., *satıcı kadına liste verdi ve kadın elma, üzüm, havuç aldı,* "the seller gave the woman a list and she bought apples, grapes, carrots") and postverbal positions (e.g., *satıcı kadına liste verdi ve kadın aldı elma, üzüm, havuç"* the seller gave the woman a list and she bought apples, grapes, carrots").

Table 1. Sample stimuli for experimental conditions

Condition A	*nested & long distance* (8 words)
[Adam [cam-dan seslen-en geniş atkı-lı kadın-a] dün sabah [kedi-y-i] göster-di]	
man.$_{\text{NOM-SG}}$ [window-$_{\text{ABL}}$ call-$_{\text{PTCP}}$ wide scarf woman-$_{\text{DAT}}$] last morning cat-$_{\text{ACC}}$ show-$_{\text{PST}}$	
'The man showed the cat last morning to the woman in the wide scarf calling from the window.'	
Condition B	*nested & short distance* (5 words)
[Adam [cam-dan seslen-en geniş atkı-lı kadın-a] t_i göster-di dün sabah [kedi-y-i]]	
man.$_{\text{NOM-SG}}$ [window-$_{\text{ABL}}$ call-$_{\text{PTCP}}$ wide scarf woman-$_{\text{DAT}}$] t_i show-$_{\text{PST}}$ last morning cat-$_{\text{ACCi}}$	
'The man showed the cat to the woman in the wide scarf who was calling from the window last morning.'	
Condition C	*linear & long distance* (8 words)
[Adam cam-dan yine geniş atkı-lı kadın-a dün sabah [kedi-y-i] göster-di]	
man.$_{\text{NOM-SG}}$ window-$_{\text{ABL}}$ again wide scarf woman-$_{\text{DAT}}$ last morning cat-$_{\text{ACC}}$ show-$_{\text{PST}}$	
'The man showed the cat again last morning to the woman in the wide scarf from the window.'	
Condition D	*linear & short distance* (5 words)
[Adam cam-dan yine geniş atkı-lı kadın-a t_i göster-di dün sabah [kedi-y-i]]	

man.$_{NOM\text{-}SG}$ window-$_{ABL}$ again wide scarf woman-$_{DAT}$ t_i show-$_{PST}$ last morning cat-$_{ACCi}$
'The man showed the cat again to the woman in the wide scarf from the window last morning.'

The auditory stimuli were individually recorded by a trained Turkish native female speaker in a phonetic booth using a dynamic microphone with a sampling rate of 44,100 Hz in waveform audio file format via Praat 6.3 (Boersma & Weenink, 2023). All octave jumps and vocalization errors were eliminated using the ProsodyPro package (Xu, 2013), which was also used to extract and analyze the acoustic properties. Experimental sentences were segmented into acoustic regions of interest for analysis of fundamental frequency, duration, and intensity to identify prosodic differences between conditions.

Each stimulus was cross-spliced using the following procedure (e.g., Degen & Tanenhaus, 2016) and recorded individually. For conditions A and C (nested and long sentences), the syntactic clauses were replaced by experimental items within the same sentence recordings to ensure consistency in prosodic structure. In the same way, conditions B and D (linear and short sentences) were formulated by cutting the target items from the original auditory recordings and putting them together in new sentence parts that match their syntactic structures. The process ensured that each experimental condition retained the appropriate linguistic characteristics for both syntactic and prosodic features, while allowing for control of the experimental design. For instance, condition B was created by replacing the clause in the recording of condition D with the experimental items used in condition A. Our acoustic analysis also confirmed that the auditory stimuli were controlled for the experiment's aims, with the mean durations of the target for long sentences being 5,166 ms for linear and 5,094 ms for nested sentences, and for short sentences, 4,898 ms for linear and 4,858 ms for nested sentences.

A professional Turkish illustrator created visual stimuli to match the auditory stimuli and transferred them into the digital environment (see Figure 1). The visual stimuli consisted of black-and-white drawings to avoid distraction. We used 480 images with different features for picture-sentence matching (Kaiser, Podesva, & Sharma, 2018). During stimulus preparation, the relevant images were positioned in a grid to ensure consistent coordinates.

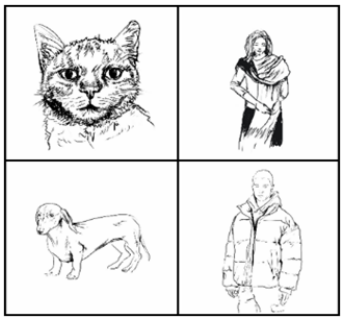


Figure 1. Example of the visual display

In Figure 1, four pictures were used in the visual display, and experimental sentences were associated with these visual pictures. The target picture, located at the top-left of the grid, refers to the specific visual item participants were expected to process. The competitor item, located at the top right, was also mentioned in the sentence but was not the direct focus of the experiment; it only shared some basic features with the target image. Figure 1 shows four matching images: The target item on the top left, the competitor item on the top right, and the distractor items on the bottom left and bottom right. The images were counterbalanced after each trial. The pictures assigned as targets and/or competitors were defined as regions of interest (ROIs) in the eye-tracking part of the experiment, and dwell time percentages within these regions were analyzed.

3.3. APPARATUS

Stimuli were presented on a 22-inch widescreen TFT LCD monitor operating at 60 Hz with a resolution of 1,680 × 1,050 pixels (501.7 mm × 337.4 mm). The screen was 600 mm from the participant, with a chin rest to minimize head movement. Eye movements were monitored using SR EyeLink 1000 (sampling rate:1,000 Hz, spatial resolution<0.5°). Only the right eye was tracked. Eye movement data were extracted using the SR EyeLink Data Viewer (version 2.4.0.198). No blink or drift correction was applied. Data were visualized and analyzed using R (R Core Team, 2024).

3.4. PROCEDURE

The study consisted of two main parts: (1) a forward digit-span task and (2) a look-and-listen task with eye-tracking. In the eye-tracking

part of the study, we used a look-and-listen task within the VWP framework (e.g., Altmann & Kamide, 2007; Degen & Tanenhaus, 2016). Participants were instructed to view a visual display while listening to spoken sentences, without being asked to provide explicit responses. As listeners process the sentence, their gaze is expected to naturally shift to visually presented referents (i.e., the target or competitor), allowing us to measure the real-time integration of linguistic and visual information without disrupting comprehension.

The experiment began with a nine-point calibration ensuring high data quality (maximum calibration error <1.50° and average calibration error <1°). Each trial consisted of drift control, fixation, and viewing. Before the start of the trial, participants listened to auditory stimuli for 2,000 ms, including a 500-ms baseline fixation period to ensure gaze stability and a 1,500-ms drift-control phase to verify calibration before proceeding to the main task. During the drift control, participants were fixated at the center of the screen, followed by a 500 ms fixation "+" at the center. The visual stimuli were displayed for 2,000 ms to allow participants to pre-process the images. The auditory stimulus was then presented for 8,000 ms, while the visual stimuli remained on the screen. The target word was paired with the target picture; competitors and distractors were presented on a white background at a visual angle of 1.28 degrees. After the visual array disappeared, a blank screen was displayed for 500 ms. Participants then had 10,000 ms to process the auditory-visual stimuli.

4. RESULTS

4.1. DATA PREPARATION AND ANALYSIS

The data were analyzed using linear mixed-effects modeling to determine the effects of structure and distance on the percentage of dwell time in the target and competitor pictures. The dwell time percentage was chosen as the leading indicator of looking times and thus online sentence processing in the visual world paradigm because it encompasses saccadic movements in addition to fixations (Kumcu & Thompson, 2020). To account for the interdependence of eye movement data in the VWP, we computed a log-transformed ratio of dwell time percentages between the target and competitor regions of interest. This dependent variable, referred to as the log ratio, was calculated for each trial using the formula: log((p(target)+0.001)/(p(competitor) + 0.001)), where p(target) and

p(competitor) represent the proportions of dwell time in the target and competitor ROIs, respectively. A small constant ($\varepsilon = 0.001$) was added to avoid undefined values. This transformation enabled direct comparison between the two regions while addressing violations of the independence assumption for proportions (Özge, Küntay & Snedeker, 2019; Ito & Knoeferle, 2023). The resulting log ratio served as the dependent variable in subsequent linear mixed-effects models.

Factors were included as fixed effects, while PARTICIPANTS and ITEMS were included as random effects in the models, provided that they improved the null model and that the analysis models converged (see details below). The contribution of a fixed effect was examined by comparing a complete model, including the effect in question, with a reduced model in which only that effect was removed or a null model without any fixed effects (Winter, 2013). Similarly, the contribution of an interaction effect (χ:y) was analyzed by comparing the complete model (χ*y) against the fixed effects model (χ+y). Mixed effects models were constructed using the *lme4* package (Bates et al., 2015). Significance values for the coefficients in the models were calculated using the t-distribution and the Satterthwaite approximation in the *lmerTest* package (Kuznetsova et al., 2017).

4.2. THE EFFECT OF THE SYNTACTIC STRUCTURE AND DISTANCE

Both random effects, i.e., SUBJECT, $\chi^2(1) = 2378$, $p > .0001$ and ITEM, $\chi^2(1) = 709.78$, $p > .0001$, improved the null model. Consequently, both were included as random effects in the subsequent models, provided that the models converged. A general CONDITION model was fitted, with the log-ratio of the dwell time percentage in the target and competitor pictures as the target variable, condition (a combination of structure and distance) as a fixed effect, and random effects. The general CONDITION model showed that the CONDITION significantly improved the null model; $\chi^2(3) = 13.03$, $p = .005$.

To further examine the effect of syntactic CONDITION with four levels (i.e., linear-long, linear-short, nested-long, nested-short) on participants' visual preference for the target over the competitor as measured by log-transformed dwell time ratios, we conducted post hoc pairwise comparisons using Tukey's method. The results showed that the linear-long condition elicited higher log ratios than the linear-short condition; $B = 0.43$, $z = 3.17$, $p = .002$. The nested-long condition also elicited higher log ratios than the linear-short condition; $B = 0.43$, $z = 3.17$, $p = .002$. The nested-short condition produced

higher log ratios than the linear-short condition; $B = 0.34$, $z = 2.46$, $p = .014$. No significant differences were found between the nested-long, nested-short, and linear-long conditions (ps > .05), suggesting similar levels of target preference across these conditions. Overall, the linear-short condition yielded the lowest relative visual preference for the target. In contrast, the other three conditions, particularly linear-long and nested-long, were associated with significantly greater target preference (see Fig. 2).

The individual DISTANCE model with DISTANCE as a fixed effect confirmed the substantial effect of structural distance, showing that DISTANCE with two levels (i.e., short and long) significantly improved the null model; $\chi^2(1) = 7.10$, $p = .008$. The complete model indicated that participants looked proportionally more at the target than at the competitor in long sentences than in short sentences; $B = 0.27$, $t = 2.69$, $p = .008$. The individual STRUCTURE model indicated that STRUCTURE with two levels (i.e., linear and nested) did not significantly improve the null model; $\chi^2(1) = 2.81$, $p = .09$. The interaction model with STRUCTURE and DISTANCE did not improve the complete model either; $\chi^2(1) = 3.001$, $p = .08$. That said, the post hoc pairwise comparisons reported above suggested that target preference was relatively greater when participants were processing nested sentences as compared to linear sentences but only in the short distance condition.

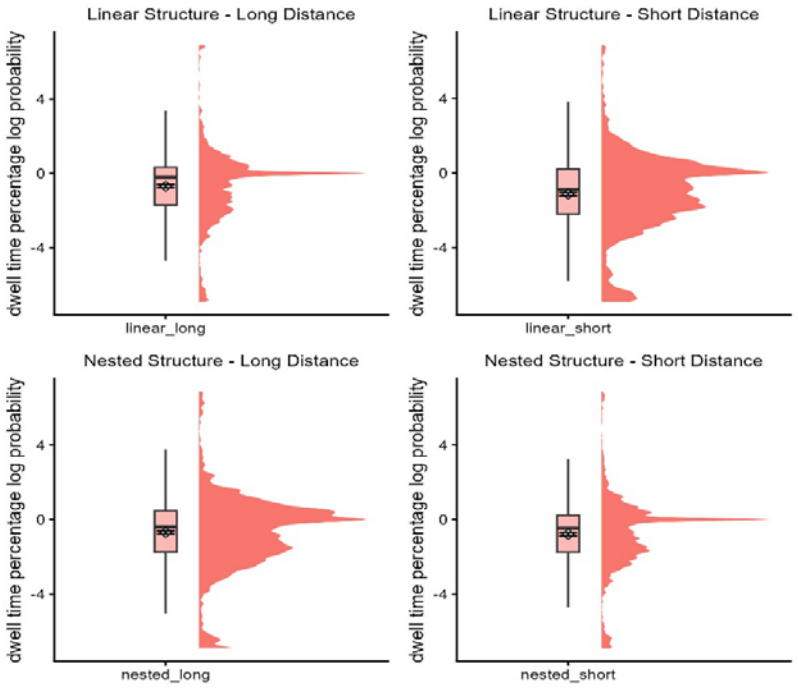


Figure 2. Violin box plots illustrating the distribution of log-transformed probability ratios log(p(target)/p(competitor)) across four conditions defined by sentence structure and dependency distance.

Positive values indicate greater dwell time on the target region relative to the competitor, while negative values indicate the opposite. The box plot displays the median (represented by the horizontal line within the box), the interquartile range (the box itself), and whiskers extending up to 1.5 times the interquartile range. The diamond-shaped marker represents the mean log ratio, and the error bars around this marker represent the 95% confidence interval.

We also analyzed the first and last runs using the same analysis procedure as described above. The first run indicates the first set of fixations on the target/competitor image after the start of the sentence. If a participant looks at the target, then at a distractor, and then back to the target, these are considered two separate runs to the target image. Results indicated that the general CONDITION model in the first run showed that the CONDITION did not improve the null model; $\chi^2(3) = 4.15$, $p = .25$, suggesting that participants did not show a significantly different preference for the target or the competitor across conditions.

The CONDITION did not improve the null model in the last run either; $\chi^2(3) = 7.23$, $p = .06$. However, post hoc pairwise comparisons using Tukey's method showed that the linear-long condition elicited higher log ratios than the linear-short condition; $B = 0.16$, $z = 2.31$, $p = .02$, as shown in the general CONDITION model. Likewise, the nested-long condition also elicited higher log ratios than the linear-short condition; $B = 0.16$, $z = 2.35$, $p = .02$.

Finally, the results showed that none of the WM indicators measured with the forward digit span task (i.e., accuracy, reaction time, memory span, and total task duration) significantly predicted the log ratio of dwell time percentage in the target and competitor pictures, suggesting no causal relationship between the two (all *p*s > .05). An interaction model with digit span accuracy and the DISTANCE did not improve the complete model either; $\chi^2(1) = 0.24$, $p = .62$.

5. DISCUSSION

The current study examined the impact of syntactic complexity and linear distance on online sentence processing in Turkish. We also addressed how auditory-visual information interacts with WM. To this end, we conducted an eye-tracking experiment using a VWP. Our results showed that participants exploit the difference in syntactic complexity between nested and linear structures and integrate them with target and competitor pictures in VWP. Long-nested structures increased dwell time on targets, while short-linear structures showed increased dwell time on competitors. However, these findings refer to separate effects of structure type rather than interaction. Specifically, no significant interaction between syntactic complexity and linear distance was observed.

Our findings regarding the individual differences in participants' WM capacities indicated that there was no significant interaction between syntactic information and WM load during online sentence processing. This finding shows that the processing of syntactic information in Turkish SRCs appears to operate independently of individual differences in participants' WM capacities. The lack of interaction between WM and syntactic information suggests that WM did not affect syntactic processing, contrary to some previous findings that have suggested a close interaction between syntactic complexity and WM (Vasishth et al., 2011; Myachykov et al., 2013; Ivanova &

Ferreira, 2018).

Our research yielded three main findings. The first hypothesis concerned the syntactic complexity effect in Turkish sentence comprehension during online sentence processing. We predicted that nested structures would be more difficult to process than linear structures during syntactic processing, particularly in target-competitor effects in VWP. This prediction is consistent with previous work supporting the SDH (Collins, 1994; O'Grady, 1997; Hawkins, 1999). This means that syntactic complexity, such as adding more nodes between the head and the gap, may indicate delays in sentence processing. However, while structure-based accounts generally imply that SRCs are more straightforward to comprehend than ORCs, our study did not find remarkable differences in gaze duration between nested and linear structures, contrary to previous studies (see Traxler, Morris, & Seely, 2002; Grodner & Gibson, 2005; Demberg & Keller, 2008; Traxler et al., 2012; Liu & Wang, 2019). The mismatch may stem from the experimental design of this study, which used nested SRCs, potentially affecting the findings differently than previous work that incorporated both SRCs and ORCs. While background research indicates that syntactic complexity is generally processed more slowly than linear distance, our findings suggest that this may not hold for SRCs in our design. This suggests that processing Turkish SRCs may depend on factors such as the structure type (single vs. double-nested) or the stimuli, pointing to future work. To conclude, our findings for the first hypothesis do not directly support the claim that syntactic complexity is processed more slowly than linear distance. Our findings confirmed a cross-linguistic view of separate processing between syntactic information and WM (Makuuchi et al., 2009; Romero et al., 2010; Cheng, 2023).

The syntactic complexity level used in this study's experimental paradigm involved manipulating SRCS with a single nested structure formed using the {-(y)An} suffix in Turkish. Our study yielded results similar to those in the existing literature regarding syntactic complexity. Makuuchi et al. (2009) found earlier processing for single- than double-nested structures in German, Romero et al. (2010) indicated separate neural correlates of syntactic complexity and WM load in English. Cheng (2023) also showed independent sentence processing for Mandarin Chinese.

Next, the second hypothesis of the current study concerned the online processing of the linear distance between the preverbal and postverbal

positions in Turkish SRCs. Earlier work has examined the linear distance and structural processing in head-final languages such as Japanese, Korean, Mandarin Chinese, and Turkish. Such studies (Miyamoto & Nakamura, 2003; Kwon, 2008; Kahraman et al., 2010; Gibson & Wu, 2013; Özge et al., 2015; Cheng, 2023) tested contrasting the predictions of sentence distance hypotheses. To test LDH's predictions regarding linear distance, our study investigated how LDH contributes to processing between preverbal and postverbal positions in Turkish. Our findings also demonstrated a significant difference between postverbal (short) and preverbal (long) positions.

Gaze duration on targets was shorter in short sentences; however, targets were longer in long sentences. Furthermore, our participants performed less efficiently with competitors on long sentences and more comfortably with short sentences. Our findings also provided evidence that the more syntactic units intervene between the filler and the gap, the more difficult it is for participants to comprehend the auditory-visual information, which supports the predictions of the LDH. Each additional syntactic unit between filler and gap increases WM load, making longer distances harder to process (Kırkıcı, 2004; Özge et al., 2015; Turan, 2018, 2020). By examining both first and last runs, we argue that we distinguish between early anticipatory or predictive processing (reflected in first-run fixations) and later integrative or confirmatory processing after more of the sentence, including the critical noun phrase, has unfolded (reflected in last-run fixations). Early in the sentence, no strong target preference emerged, indicating a lack of early anticipatory looking. This suggests referential information had not yet accumulated sufficiently to discriminate between interpretations. Pairwise differences suggest structural distance influenced final interpretations. Longer sentences, whether linear or nested, yielded greater target preference than short linear sentences. The effect in the final run suggests delayed reference resolution in audiovisual processing.

It is also important to emphasize another point concerning the second hypothesis. The effect of structural distance in Turkish SRCs was less robust than the effect of linear distance (long vs. short sentences). This syntactic position involves rightward movement, which has received less attention in the background studies (Kornfilt, 1998; Manetta, 2012) than leftward movement (Mahajan, 1990; Kidwai, 2000). Leftward movement is generally associated with the active filler strategy (Frazier, 1987; Frazier & Clifton, 1989), where participants

exploit the “filled gap” effect during sentence processing. In our study, however, the potential gap position shows a rightward bias, with participants associating the gap with the preverbally positioned filler. Accordingly, the filler is located preverbally, while the gap is positioned postverbally in the sentence. As is well known, this rightward movement position is typically defined as tail or background information and does not directly provide new information. In Turkish, the constituents in this position allowed us to alter the units in the canonical SOV word order, which exist in six possible permutations (i.e., SOV, SVO, OSV, OVS, VSO, VOS) (Kural, 1992; Kornfilt, 1998). The results of our study imply that SVO takes longer to process than SOV in the VWP during sentence processing. On the other hand, it is worth noting that our study employs ditransitive verbs, in which the RC alters the indirect object, and the direct object is positioned either preverbally or postverbally. One of the two objects was consistently positioned preverbally in all experimental conditions. This may have influenced our interpretation of the observed difference in online processing difficulty between SVO and SOV structures in Turkish sentences. While this finding is significant, it may be viewed as stronger given the experimental design of the test items; this should be taken into account when interpreting the results. So, this issue leads us to conclude that postverbal elements in Turkish have reduced cognitive processing load in WM relative to preverbal constituents. Since the postverbal elements generally interact with background or tail information in a sentence rather than new information (i.e., sentence focus), this results in lower memory and processing costs. Consequently, participants must hold less immediate information in WM when processing postverbal elements, reducing cognitive load. In contrast, preverbal elements require more cognitive resources for integration and processing than postverbal elements, thereby increasing cognitive load in WM.

Using a forward digit-span task, our third hypothesis examined the interplay between syntactic processing and participants’ WM capacity. Regarding assumptions about the processes underlying online sentence comprehension, one cognitive model is directly related to a single sentence interpretation (Norman, Kemper, & Kynette, 1992; Just & Carpenter, 1992; Weighall & Altmann, 2011), whereas another cognitive model refers to a separate approach to WM load (Fedorenko et al., 2006; Makuuchi et al., 2009; Romero et al., 2010; Cheng, 2023). Our experimental model suggests that individual differences in WM

may not directly affect how people comprehend sentences under varying workloads. The findings from Turkish sentence processing support a cross-linguistic view of the independent processing between syntactic information and WM load. Our WM task tested only individual differences in memory storage resources for language-specific processing; however, we must note that the subcomponents of WM load (e.g., recall, recognition, retrieval) may also be responsible for sentence interpretation.

Furthermore, LDH posits that the syntactic violation for the moved filler is maintained in WM, while the structural interaction continues for sentence comprehension. Our results were expected to support the increased processing load between preverbal and postverbal positions, as the participants encounter a processing difficulty when the target item moves to a non-canonical position. This assumption implies that while the filler is being processed in WM, the parser continues to add new information for the gap position. As mentioned above, individual differences in participants' WM capacity are greater when processing ORCs than SRCs. Previous work on syntactic complexity does not provide direct evidence for processing differences as syntactic complexity increases or decreases. As we discussed earlier, our manipulation for syntactic structure maintains a single nested violation for SRCs, which are much easier to process than ORCs, both for Turkish (see Kırkıcı, 2004; Aydın & Cedden, 2010) and for several other languages (see Tarallo & Myhill, 1983; Gibson, 1998; O'Grady et al., 2003). This study does not provide direct evidence for how individual differences might influence the WM load during sentence comprehension. In conclusion, this study does not directly provide evidence for how individual differences might affect the participants' WM load during online sentence processing. Future work could address how participants' WM capacity interacts with syntactic complexity and the distance effect in Turkish.

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List of abbreviations

LDH- Linear Distance Hypothesis

ORCs- object relative clauses

RCs- relative clauses

ROIs- regions of interest

SDH- Structural Distance Hypothesis

SOV- Subject-Object-Verb

SRCs- subject-relative clauses

SVO- Subject-Verb-Object

VWP- Visual World Paradigm

WM- working memory

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