Published in final edited form as:
Cognition. 2013 December ; 129(3): 544–562. doi:10.1016/j.cognition.2013.08.007.

Ways of looking ahead: Hierarchical planning in language production

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Abstract

It is generally assumed that language production proceeds incrementally, with chunks of linguistic structure planned ahead of speech. Extensive research has examined the scope of language production and suggests that the size of planned chunks varies across contexts (Ferreira & Swets, 2002; Wagner et al. 2010). By contrast, relatively little is known about the structure of advance planning, specifically whether planning proceeds incrementally according to the surface structure of the utterance, or whether speakers plan according to the hierarchical relationships between utterance elements. In two experiments, we examine the structure and scope of lexical planning in language production using a picture description task. Analyses of speech onset times and word durations show that speakers engage in hierarchical planning such that structurally dependent lexical items are planned together and that hierarchical planning occurs for both direct and indirect dependencies.

Keywords

Language production; planning scope; hierarchical planning

Introduction

At the surface form, spoken language is expressed as a linear sequence of linguistic symbols, or words. By contrast, the underlying structure of this sequence of words is, in Lashley's (1951) words, a "series of hierarchies of organization", evident at multiple levels of linguistic structure, including grammatical, lexical and phonological structures. Lashley's arguments with respect to language were largely in response to a view of language as an incremental, associative production of linguistic forms. Such arguments are inconsistent with now well-known evidence that speech errors typically obey the phonotactic and syntactic regularities in the language (Dell, Reed, Adams, & Meyer, 2000; Garrett, 1975), suggesting that the elements of what eventually becomes a linear sequence are planned together at some higher level of organization.

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One level of representation with clearly non-linear elements is the *message*, which is the starting point for language production and represents the speaker's communicative intent. The message is initially generated in a non-verbal form, and then undergoes linguistic encoding so that it can be articulated (Bock & Levelt, 1994; Levelt, 1989). Linguistic encoding involves multiple levels of processing including retrieving lemmas corresponding to the concepts in the prepared message (i.e., lexical items that are not specified for the phonological structure), building syntactic structure, and retrieving morpho-phonological forms. It is generally accepted that production proceeds incrementally (Bock & Levelt, 1994; Kempen & Hoenkamp, 1987; Levelt, 1989). That is, speakers do not formulate an entire utterance before speaking. Instead, speech is initiated once a minimal chunk of an utterance is retrieved, with preparation of subsequent structures continuing as speaking unfolds in time. This applies to all levels of the production system. However, the scope of planning has been known to vary at different levels of the production system with a wider scope at earlier levels than at later levels (*e.g.,* Wundt, 1900, but see Brown-Schmidt & Konopka, 2008, for evidence that the scope of message planning can be as small as a single word). In the present study, we examine the scope of planning at the grammatical encoding level, which involves lemma selection.

Important for understanding the time-course of planning is the observation that the linear order in which words appear is often not isomorphic to the syntactic relationships between words. These syntactic relationships can be expressed in a hierarchical structure like a syntactic tree. Within a tree, words that are semantically or syntactically related maintain closer connections than words with more distant syntactic relationships. For example, the verb and the subject of a sentence are dependent on each other and thus, hierarchically proximate to each other. However, words that are hierarchically close to one another are not always adjacent in the linear order of the sentence. In the sentence “The boy threw the ball.”, the subject phrase “the boy” and its verb “threw” are close together linearly. By contrast, in the sentence “The boy on the left threw the ball.”, the subject and the verb are linearly distant because of an intervening prepositional phrase “on the left”. However, as illustrated in Figure 1, the hierarchical distance between the subject phrase and its verb is identical in both sentences.

Research on language production to date has focused primarily on how far ahead an utterance is prepared before speech (*e.g.,* Garrett, 1975; Smith & Wheeldon, 1999; Griffin, 2001; 2003; Martin, Crowther, Knight, Tamborello II, & Yang, 2010; Meyer, Sleiderink, & Levelt, 1998; Meyer & van der Meulen, 2000; Brown-Schmidt & Konopka, 2008). Here, our focus is on the *structure* of advance planning, specifically, whether a speaker's scope of lexical planning depends primarily on the hierarchical structure of the sentence or whether lexical planning is primarily constrained by the linear surface order in which the words appear. In addition, in contrast to much of the work on advance planning which focuses on planning before speaking begins, we also examine the processes by which planning proceeds after speaking has already begun.

Linear incrementality versus Hierarchical incrementality

It is generally assumed that speech is initiated once the lexical representation of a minimal chunk of an utterance is retrieved. Lemmas associated with material that will appear later in an utterance are retrieved after speaking begins (as the earlier part of the utterance is being produced). However, there is no consensus on how far ahead lexical planning proceeds before speaking. This disagreement is tied partly to whether lemmas are selected in a word-by-word fashion constrained by the availability of concepts to express components in the message (linear or lexical incrementality) or whether lemma access is constrained by the structural relationships between lexical items (hierarchical or structural incrementality).

Evidence for Linear incrementality—The linear (or lexical) incrementality view assumes that lexical planning is guided by the availability of lexical concepts. The most accessible concept is encoded first and thus is produced early in the utterance. The size of the increments is as small as a lexical word (Griffin, 2001; 2003; Griffin & Bock, 2000; Meyer et al., 1998). For example, Griffin (2001) provides evidence for a lexically incremental planning scope in word selection and phonological encoding. In this study, speakers described a scene with three pictured objects using the sentence frame *The A and the B are above the C*. Codability and frequency are known to affect the difficulty of lexical selection and the difficulty of the retrieval of a word's pronunciation, respectively. Speech latencies were modulated only by the codability (name agreement) and frequency of the first object (A), suggesting that the lexical item for object A was planned ahead of and independently of those of later elements B and C, even though B was in the same complex noun phrase as A. Such evidence is consistent with a linearly incremental view in which lexical planning proceeds sequentially for each unit, and the planning of an earlier unit does not always require planning ahead the material to be produced later in the utterance.

Evidence for hierarchical incrementality—Other evidence suggests that in some circumstances, planning units at the lexical level can be larger than a single lexical item such that words that appear later in the surface structure *are* planned with earlier words. The scope of lexical planning can be as large as a syntactic phrase (Allum & Wheeldon, 2007; 2009; Martin et al., 2010; Smith & Wheeldon, 1999; Wheeldon, Ohlson, Ashby, & Gator, 2013) or a single clause (Meyer, 1996). Evidence for a broader scope of planning is consistent with hierarchical incrementality in that the number of lemmas retrieved prior to speech is often constrained by the grammatical structure of a sentence. Wheeldon and colleagues (Allum & Wheeldon, 2007; 2009; Smith & Wheeldon, 1999; Wheeldon et al., 2013) have shown that the scope of lexical planning is modulated by the structure of a sentence initial grammatical phrase, with more lemmas retrieved when sentences begin with a coordinate noun phrase than with a simple noun phrase. Other findings (Lindsley, 1975; Kempen & Hujibers, 1983) suggest that advance planning at the lexical level may proceed beyond the initial subject noun phrase to include the selection of a verb lemma. This view follows from Ferreira (2000)'s TAG (tree-adjoining grammars)-based approach to language production, in which the retrieval of a lexical head results in the retrieval of an elementary syntactic tree containing its argument positions. When the lexical head is a verb, it projects a structure for the entire clause. Lexical heads like nouns and prepositions generate a structure for the phrase. Because the entire sentence frame becomes apparent only after the verb is selected, the subject noun is not grammatically encoded as a subject until after the retrieval of the verb. Thus, the TAG-based approach to language production predicts that a verb lemma and the frame of a clause projected by the verb are prepared in advance. This view is supported by an empirical finding from Lindsley (1975) in which participants described a picture illustrating a transitive action, using different utterances consisting of just the subject (*e.g., The man*), just the verb (*e.g., greeting*), or both the subject and the verb (*e.g., The man is greeting.*). While participants took longer to initiate the subject-verb utterance than the subject-only utterance, the subject-verb utterance did not differ from the verb-only utterance in speech initiation time, suggesting that the verb is obligatorily planned before speech onset when an utterance contains a verb. However, this finding was not fully supported by Schriefers, Teruel, and Meinshausen (1998), who used a picture-interference paradigm to test whether access to a verb lemma is an essential part of advance grammatical encoding. The authors manipulated the relative position of the verb in German, which has a flexible word order. Inconsistent with the claim by the TAG-based approach to language production and the Lindsley's finding described above, Schriefers et al. (1998) found that speech initiation times were affected by a semantic distracter related to the verb only when the verb appeared in a sentence-initial position. The effects were not replicated when the verb was produced in an utterance-final position. These findings suggest that at least in some circumstances, verb access is not necessarily performed before speech onset.

Other evidence from picture-description tasks is consistent with hierarchical planning. Meyer (1996) asked participants to describe two objects using the frame "*The A is next to the B.*", given displays containing an auditory distracter that was either semantically or phonologically related to A or B. Distracters that were semantically related to A or B increased speech initiation times, but a phonological distracter affected speech latencies only when it was related to A. The findings suggest that lemmas (but not the phonological structure) for both nouns may be retrieved before speech onset, suggesting that, at least for this type of verb (*i.e*., be), lexical selection for all dependents may be performed simultaneously.

In the current study, we revisit the question of whether lexical planning is mediated by the dependency relationships between words by explicitly manipulating the dependency relationships between the elements within a clause in a single study. By explicitly manipulating the hierarchical structure, we attempt to disentangle its effects from those of the linear structure. In addition, we examine how extensive the scope of hierarchical planning can be. To this end, the current study uses a construction in which a lexical head is associated with more than one dependent.

The current study

The present research investigates whether the scope of lexical planning in language production is mediated by hierarchical relationships, or whether lexical planning scope is mediated by the linear surface order of an utterance. We test this hypothesis by explicitly manipulating structural dependencies using relative clause attachment ambiguities (e.g., the student of the teacher who is raising her hand). In this type of sentence, the complex noun phrase is followed by a relative clause. The complex noun phrase consists of a head noun (*the student*) and a prepositional phrase (*of the teacher*) that is dependent on the head noun (as an argument in our stimuli). Ambiguity arises because there is more than one potential head noun in the complex noun phrase for the relative clause (*who is raising her hand*) to modify. In one structure, the relative clause modifies the head noun of the complex noun phrase (*i.e*., *student*). We will call this the high noun because it is higher in the syntactic tree than the noun in the prepositional phrase. In this syntactic structure (illustrated in Figure 2a), the relative clause and the high noun are hierarchically proximate. In the other structure (Figure 2b), the relative clause is associated with the noun in the prepositional phrase (*i.e*., *teacher*), which we will call the low noun. In this structure, the relative clause is not hierarchically proximate to the high noun. Importantly, the high attachment and low attachment sentences differ in whether the relative clause is in a dependency relationship with the high noun or the low noun, but they are identical in word order. The high noun is followed by the low noun, which is then followed by the relative clause in both interpretations. Thus, we can use this construction to manipulate the dependency relationship between the relative clause and its heads while holding the linear order constant across the two structures. By measuring whether the different constructions affect the timing of production, we can evaluate whether lexical planning proceeds in a strictly sequential order or whether it depends on hierarchical structure, while holding the surface form of the utterance constant.

The relative clause construction also allows us to explore how broad the scope of planning for dependents is. In this construction, the dependency relationship between the high noun and the relative clause differ between the high attachment and low attachment structures. In the high attachment structure, the relative clause and the low noun are directly dependent on the high noun. By contrast, in the low attachment structure, the relative clause is dependent on the high noun indirectly through an attachment to the low noun, which is directly dependent on the high noun.

The difference in hierarchical structure between the high attachment and low attachment structures enables us to test different versions of the hierarchical view, each of which assumes a different scope of hierarchical planning. In the high attachment interpretation, the relative clause is directly dependent on the high noun. By contrast, in the low attachment interpretation, there is only an indirect relationship between the high noun and the relative clause. If lexical planning is moderately hierarchical, the scope of hierarchical planning at the lexical head may be limited by including only the material that is directly dependent on the head. In this case, lemmas for the low noun and the relative clause should be accessed at the same time as a high noun lemma in the high attachment structure, but the lexical planning of the relative clause should be delayed until after a low noun lemma is accessed in the low attachment structure. In the low attachment structure, the low noun is directly dependent on the high noun as in the former structure. Alternatively, the scope of lexical planning could be wider and include both direct and indirect dependents. On this radically hierarchical account, lemma representations of the low noun and the relative clause noun should be accessed at the same time in both interpretations because both the low noun and the relative clause are either direct or indirect dependents of the high noun in both interpretations.

A final possibility is that lexical planning proceeds in a strictly sequential order with no consideration of hierarchical structure. On this linear account, a high noun lemma should be accessed prior to speech onset, a low noun lemma should be accessed at the high noun, and a lemma representation of the relative clause should be planned at the low noun, regardless of the syntactic structure.

In sum, the moderately hierarchical account predicts that lemma representations of the relative clause will be accessed earlier in the high attachment structure than in the low attachment structure. By contrast, neither the radically hierarchical nor the linear account predicts *differences* in the timing of selecting a lemma representation of the relative clause between the high attachment and low attachment structures. Importantly, however, the radically hierarchical account, but not the linear account, predicts early planning of the relative clause at the lexical level (regardless of structure). Figure 3 presents a diagram illustrating the hypothesized effect of attachment condition (high vs. low) on the timing of lexical planning during the articulation of each part of the sentence, separately for each of the three accounts described above.

Figure 3 illustrates how the competing accounts make differing predictions for how attachment affects lexical planning at the high noun. Note that the figure illustrates relative differences between the high attachment and low attachment conditions. As we can see in Figure 3, neither the linear account nor the radically hierarchical account predict differences in planning cost between the high attachment and low attachment structures during the articulation of the high noun. Thus while more words are being selected at the high noun in the radically hierarchical account than at other points in the sentence, there is no *difference* between low attachment and high attachment in the number of words that are selected. By contrast, according to the moderately hierarchical view, the high noun region should involve more effortful planning in the high attachment structures. In the high attachment structure, both low noun and relative clause lemmas are accessed together, whereas in the low attachment structure, a lemma representation of the relative clause is not selected until after the planning of the low noun.

Finally, note that on all three accounts, speech onset times are not expected to be affected by the hierarchical structure of the utterance because a high noun lemma is always selected first. However, the planning of high attachment structures might be more difficult than that of low attachment structures at the conceptual or syntactic level because high attachment is less preferred in English (Cuetos & Mitchell, 1988; Gilboy, Sopena, Clifton, & Frazier, 1995, but see Swets, Desmet, Hambrick, & Ferreira, 2007 who find no dominant attachment preferences in English), independent of the difference in hierarchical structure. The difference in structural preferences might affect speech onset times and/or overall articulatory duration of the utterance with longer initiation times and word durations in the high attachment structure than in the low attachment structure. We will return to this issue below.

Planning before speech vs. after speech

Previous work has assessed production processes by examining the latency to begin speaking, which reflects planning *before* articulation. However, if preparation of utterances continues after speech onset, we might expect to find evidence of how speakers engage in planning *while* they are articulating.

In order to examine planning-while-speaking, the current study uses utterance durations as a dependent measure in addition to speech latencies in order to examine how grammatical encoding is implemented *during* articulation as well as before speech. We assume that longer word durations reflect difficulty of planning upcoming material. The logic behind this assumption is similar to arguments that speakers include optional complementizers (Ferreira & Dell, 2000) or disfluencies in order to provide extra planning time (Brown-Schmidt & Tanenhaus, 2006; also see Jaeger, 2010), and increase speech latencies when the beginning of an utterance is complex and thus requires extra planning. Specifically, we hypothesized that speakers may increase articulatory durations to buy sufficient time to plan the next part of an utterance.

Evidence consistent with the hypothesis that articulatory durations reflect planning efforts comes from Kawamoto, Kello, Jones, and Bame (1998), who found that initial consonant durations were affected by the regularity of the vowel pronunciation. The durations of the initial consonant in a word were shorter when it was followed by vowels with regular spelling-to-sound correspondences (*e.g., soak*) than by those with irregular correspondences (*e.g., sew*). Similarly, Ferreira and Swets (2002) observed a relationship between utterance duration and planning difficulty in the production of arithmetic sums. When a response deadline forced speakers to plan incrementally, arithmetic problem difficulty affected utterance durations as well as speech latencies, even when the sum occurred at the end of the sentence. These findings are important because they suggest that articulatory durations may be used as an index of how planning is implemented during speech.

Experiment 1

Experiment 1 examined whether the form and scope of lexical planning in language production is modulated by hierarchical structure or by linear order. In order to address this question, we designed an interactive task in which participants described a designated target referent in the visual display to an addressee, using ambiguous relative clause constructions like Click on the fork of the king (who's/that's) below the apple. Two different types of displays were used to elicit target sentences with the two types of attachment (Figure 4A: high attachment, Figure 4B: low attachment). In the high attachment display, the relative clause object (e.g., apple) was below (or above) the high noun object (e.g., fork). In the low attachment display, it was below (or above) the low noun object (e.g., king).

We also manipulated the codability (*i.e.*, name agreement) of the relative clause noun (e.g., apple vs. hat/cap). Codability of nouns is thought to reflect difficulty in lexical access, due to greater interference during lemma selection when a to-be-mentioned object is associated with more than one possible name (Griffin, 2001). Speakers take more time to select words for less codable objects than for those with a single possible name. We hypothesized that effects of codability would allow us to index points of planning of the noun in the relative clause.

The high attachment and low attachment utterances were compared for speech initiation times and durations of each of the following regions of critical utterances.

(1) [$_{Preamble}$ Click on the] [$_{A}$fork] [$_{of\ the}$ of the] [$_{B}$ king] [$_{below\ the\ C}$ (who's/that's) below the apple.]

Method

Participants

Twenty native English speakers from the University of Illinois at Urbana-Champaign participated in the study. Participants received either partial course credit or payment ($8) for their participation.

Materials

There were sixteen critical displays. The target sentence frame was Click on the A of the B (who's/that's) above/below the C. Each of the sixteen critical displays was presented in both high attachment and low attachment conditions (Figure 4). Target referents appeared equally often in each of the four scenes. In each scene, two clipart images of objects were in positions A and C. In position B, there was always a clipart image of a person who was easily identifiable by occupation. Referents A and B were in a possessive relationship (*i.e.*, the A of the B), which was indicated by a diagonal line in the visual display (*e.g., the fork of the king*). To make all three referents informative in identifying target referents in both interpretations, the visual display was designed to contain four scenes. A scene that included a target referent (indicated by a circle) was contrasted with each of the other scenes for one of the referents, which required all three referents to be included in the instructions. The layout of the visual display was designed so that within each scene, each of the referents was approximately equidistant from the other two referents.

In addition to attachment type, the codability of object C was manipulated as a between-items factor. Eight items with high codability (apple, baby, cake, window, table, bowl, bottle, and shoe) and eight items with medium codability (hat/cap, coat/jacket, (wine) glass, (frying) pan, tray/platter, weights/barbells, chest/trunk, and TV/television). These items were adapted from Griffin (2001). Half of the 16 critical displays had highly codable objects in position C while the other half had objects with medium codability.

In addition to 16 critical items, 64 distracter items produced in four sentence frames shown in (2) below were designed to prevent speakers from developing an atypical planning strategy due to the repeated production of a single structure.

(2)

a. All the images are the same.

b. There are no images.

c. Click on the pear.

d. Click on the red socks.

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Following Allum and Wheeldon (2007), we used 16 distracter trials in which the visual display contained four identical pictured images (2a) and another 16 distracter trials in which the visual display consisted of no images (2b). In the 32 remaining displays, four pictured images were presented. Participants described a target referent indicated by a circle as on critical trials. In 16 of those displays, four images were all different so participants described the target using a simple noun phrase like (2c). In the other 16 displays, two of four images represented the same objects in different colors, which led speakers to use a color adjective before the head noun as in (2d).

The experimental session was blocked. Each block consisted of 16 critical displays and 64 distracter displays. Each participant saw both versions of each critical display across blocks. For half of the items, the high attachment version was presented in the first block and for the other half, the low attachment version was presented first. The distracter items were repeated across blocks. The presentation order of the experimental trials and distracters was pseudo-randomized so experimental items did not appear on the first trial of any block and there were at least three distracters intervening between experimental items. Trials were presented in an identical order in both blocks. Attachment type was counterbalanced across lists, resulting in two different lists. We created two additional lists by reversing the order of trials. Each participant completed the trials in a single list.

Procedure

Participants were informed that they would be engaged in an interactive task with an experimenter, and that they would play the role of the speaker. Participants were seated at a computer and read the instructions on their own computer displays. All instructions were presented with examples. In the instructions, participants were told that the pictures connected by a diagonal line indicated a possessive relationship (*e.g., the fork of the king*) and those arranged vertically represent a spatial relationship (e.g., *the apple above the fork* (Figure 4A), *the apple above the king* (Figure 4B)). Speakers were explicitly told that only vertically aligned objects were to be described in a spatial relationship (*e.g*., in Figure 4A, the apple is above the fork, but not above the king or dancer.). In order to encourage speakers to produce instructions using the target sentence frame (e.g., Click on the fork of the king (who's/that's) below the apple), speakers were told to: 1) mention all of the objects as well as their possessive and spatial relationships and 2) produce descriptions in a single sentence. The task began with two practice items; if speakers produced alternative structures or missed one of the objects during practice, they were corrected. The role of the addressee was played by an experimenter. The experimenter sat at a separate computer.

At the beginning of each trial, a 5 second preview period was designed to provide speakers with time to apprehend the display before speaking. After 5 seconds, the speaker saw a circle that indicated the target referent. The speaker described the target referent for the addressee using the target sentence frame Click on the A of the B (who's/that's) above/below the C. The addressee viewed the same four scenes, and clicked on the target referent according to the speaker's instructions. The next trial began immediately after the addressee's selection. The speaker's instructions were recorded to a computer using a microphone.

Analysis

In this and the following experiments, speech onset latencies and the durations of each region were analyzed using Praat speech analysis software (Boersma & Weenink, 2009). The onset of each utterance and the onset and offset of each critical region within an utterance were determined based on visual inspection of the waveform and spectrogram. Speech onset latencies were measured as the duration between the onset of the visual display (indicated by a beep) and the onset of the utterance. The duration of each critical region included the duration of the words as well as any silent pauses that followed. Utterances were excluded from further analysis if the speaker used different lexical items across attachment conditions. Utterances containing disfluencies (e.g., repeats, repairs, filled pauses) were also excluded from analysis. Although disfluencies provide extra planning time, their presence necessarily increases word duration. Thus, in order to ensure that the effects of planning on duration were not simply attributable to disfluency, we excluded disfluent trials. Note that a similar pattern of results were obtained (presented in appendix A) when disfluent trials were included in the analysis.

In all experiments, speech latencies and word durations were measured in milliseconds and then were log transformed to correct skew. The log-transformed values were analyzed using a multi-level model with attachment (high attachment vs. low attachment), codability (medium codability vs. high codability) and the interaction between attachment and codability as fixed effects. The predictor variables were coded using mean contrast coding. Parameter estimates were obtained by maximum likelihood estimation, and *t*-values greater than 2 were treated as significant (Baayen, 2008). For each model, the random effects structure was determined by stepping backwards from the maximal random effects model, which contained by-participant and by-item random intercepts, a by-participant random slope for the interaction between attachment and codability, and a by-item random slope for attachment. When excluding a random effects parameter led to a significantly worse fit of the model in likelihood ratio tests ($p<.05$), the more complex model was selected as the final model. Because codability was manipulated as a between-items factor, lexical items varied across codability conditions. In order to control for lexical differences between the two codability conditions, the frequency and the length of the critical words (*i.e.*, A, B, & C) were added to the final model as control variables. In order to control for practice effects, trial number was also included as a control variable.

Predictions

The three planning accounts make differing predictions as to the effect of the codability of object C (*i.e.*, the noun in the relative clause). First, the linear account predicts no effect of codability. On this account, speakers should plan the low noun during the articulation of the high noun with no look-ahead planning for the relative clause. Thus, the duration of the high noun should not be affected by the codability of the relative clause noun. Second, the moderately hierarchical view predicts an interaction between codability and attachment on the duration of the high noun. The relative clause is a direct dependent of the high noun only in the high attachment structures. The scope of advance planning at lexical heads should be limited to direct dependents with the relative clause planned at the high noun in the high attachment structures and at the low noun in the low attachment structures. Thus, during production of the high noun, the codability effect should be observed in high attachment, but not in low attachment, resulting in a reliable attachment by codability interaction. Finally, the radically hierarchical account predicts look-ahead planning of the relative clause in both conditions, resulting in a main effect of codability with no interaction because both the low noun and the relative clause are dependent on the high noun either directly or indirectly, in both interpretations.

Results

95 high attachment and low attachment pairs in which different lexical items were used across conditions were excluded from the analysis. Twenty-six additional trials were excluded due to disfluency, including repeats, repairs, filled pauses, and prolongation of “the” (*i.e.*, “thee”) in at least one of the attachment conditions (see appendix B for the

number of disfluent trials by condition). As a result, 199 out of 320 high attachment and low attachment pairs (20 subjects × 16 items) in which the instructions were produced using a target sentence frame with matched lexical items across conditions were included in the analysis.

Table 1 presents a summary of the speech latency and duration measures. The parameter estimates and final model designs for each of the measures are summarized in Table 2.

Speech latency—The parameter estimates for speech latency indicates that there was a reliable effect of attachment with longer latencies taken to initiate the high attachment structures (HA: 1328ms vs. LA: 1254ms, =0.050, SE=0.024, *t*=2.1). There was no effect of codability (=0.003, SE=0.029, *t*=0.1), nor was there a reliable interaction (=−0.018, SE=0.048, *t*=−0.4). The lack of a codability effect suggests that the effect of attachment on latency is unlikely to be due to the difference in the timing of lexical planning of the relative clause between the high attachment and low attachment structures. We return to this point later in the Discussion.

Region before the high noun—The model for the duration of "Click on the" shows that, consistent with the latency measure, the effect of attachment was significant (HA: 658ms vs. LA: 620ms, =0.049, SE=0.023, *t*=2.2). There was no main effect of codability (=0.038, SE=0.034, *t*=1.1). The attachment × codability interaction was not significant (=0.003, SE=0.046, *t*=0.1).

High noun—A significant effect of codability on the high noun (Medium: 637ms vs. High: 612ms, =0.124, SE=0.034, *t*=3.7) was due to longer duration when the noun in the relative clause (C) had medium codability than when it was highly codable. There was no main effect of attachment (=0.017, SE=0.024, *t*=0.7)[1], nor was there a significant interaction (=0.024, SE=0.049, *t*=0.5). These findings are consistent with the prediction of the radically hierarchical account.

Regions after the high noun—None of the predictors significantly predicted the duration of "of the" (attachment: =−0.014, SE=0.029, *t*=−0.5, codability: =0.017, SE=0.048, *t*=0.4, interaction: =−0.056, SE=0.059, *t*=−0.9).

There was a significant effect of attachment on the duration of the low noun: there was greater lengthening in the high attachment structure than in the low attachment structure (HA: 835ms vs. LA: 784ms, =0.074, SE=0.028, *t*=2.7). In addition, a significant effect of codability was due to longer low noun durations in the medium codability condition compared to the high codability condition (Medium: 825ms vs. High: 794ms, =0.110, SE=0.044, *t*=2.5). The interaction was not significant (=−0.091, SE=0.056, *t*=−1.6).

The pattern of the results for the duration of the relative clause was similar to that for the duration of the low noun. The effects of attachment (HA: 1083ms vs. LA: 1023ms, =0.057, SE=0.019, *t*=2.9) and codability (Medium: 1115ms vs. High: 994ms, =0.151, SE=0.061, *t*=2.5) were both significant, and there was no reliable interaction (=0.020, SE=0.039, *t*=0.5).

[1]In a preliminary study in which we manipulated attachment type but not codability and used a simpler visual display, we did find a significant effect of attachment on the duration of the high noun, with a longer duration in high attachment structures than in low attachment structures. While potentially consistent with moderately hierarchical planning, we could not draw strong conclusions from this preliminary study due to confounding variables including differences in structural frequency and picture layout between the conditions. It was also unclear which levels of planning the effects were tied to. The details of this study can be found at http://labs.psychology.illinois.edu/CaLL/publications.html

Discussion

The results of Experiment 1 provide evidence for extensive planning at the lexical level beyond the immediate next word. The significant effect of codability on the length of the high noun suggests that lemmas for multiple dependents were selected at the lexical head, supporting the radically hierarchical account. Effects of attachment type were spread throughout the utterance, and included an effect of attachment type on speech onset latencies, as well as an effect of attachment type on the duration of the region before the high noun, the low noun length, and the relative clause length. The fact that the attachment effect was significant at early regions of the planning (i.e., at speech onset and in the region before the head noun) is consistent with a very high degree of look-ahead in planning, suggesting that speakers had decided on a structure prior to speaking. The extent of the effect across the sentence suggests that attachment type modulated the overall difficulty of planning processes both before and during speaking. In English, a low attachment interpretation for the target structure is preferred over a high attachment interpretation (Cuetos & Mitchell, 1988). Thus, producing a high attachment message to fit the target sentence frame may have been more difficult compared to a low attachment message.

Furthermore, the attachment effect on the duration of the low noun may reflect that speakers used prosodic phrasing to mark the difference in the hierarchical structure of the relative clause between the high attachment and low attachment structures. Previous comprehension studies have shown that listeners interpret a prosodic break before the ambiguous phrase (i.e., the relative clause) as signaling high attachment (Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991; Watson & Gibson, 2005). Prosodic breaks are signaled by acoustic cues of pre-boundary word lengthening, changes in pitch, and pauses. Thus, longer duration of the low noun and following pauses can provide a signal to high attachment. In the current study, the difference in the duration of the low noun between the high attachment and low attachment structures may have been mediated by the speaker's planning of prosodic structure, which reflected hierarchical dependencies.

Overall, the results of Experiment 1 are consistent with the radically hierarchical account, suggesting that the scope of lexical planning at the head noun can be extensive and can include both direct and indirect dependents. The lack of an attachment effect at the high noun in Experiment 1 is inconsistent with the moderately hierarchical view, and the finding that the duration of the high noun was affected by the codability of the relative clause noun in both attachment conditions is consistent with the radically hierarchical account.

In Experiment 2, we test whether our findings extend to situations in which speakers have less planning time by eliminating the five-second preview period.

Experiment 2

One reason there may have been such striking evidence for radically hierarchical planning in Experiment 1 is that speakers were given plenty of time to prepare the full sentence prior to speaking, both during the 5-second picture preview, and during the preamble phrase, *Click on*. The goal of Experiment 2 is to test whether early effects of the codability of the noun in the relative clause was due to early initiation of lexical access processes during the preview. In Experiment 2, we minimized preemptive planning by removing the 5-second preview period that was present in Experiment 1, and by eliminating the preamble phrase (“Click on”) from the target sentence frame. If the results from Experiment 1 extend to less fully prepared speech, we should replicate the effect of the relative clause noun's codability in Experiment 2.

Method

Participants

Twenty native English speakers from the University of Illinois at Urbana-Champaign participated in the study either for partial course credit or for payment ($8). None of the participants participated in the earlier experiment.

Materials and Procedure

The critical displays were the same as used in Experiment 1 except that two of the objects used in the high codability condition were replaced with other highly codable objects (bowl→pizza, bottle→ tomato) because speakers were inconsistent in the use of labels for those items. On each trial, speakers described target referents (indicated by a circle) using a complex noun phrase followed by a relative clause without a preamble phrase. Thus, a target sentence frame was *the A of the B (who's/that's) above/below the C*.

The experimental procedure was identical to that of Experiment 1 except that the target referent was indicated at the onset of the visual display with no delay.

Results

215 out of 320 high attachment and low a ttachment pairs with matched lexical items across attachment conditions were included in the analyses. 105 high attachment and low attachment pairs were excluded due to the use of disfluencies (14 pairs, see appendix B for number of disfluent trials by condition) and the use of mismatching lexical items across conditions (91 pairs). The data were analyzed in the same way as in Experiment 1. Table 3 shows a summary of the results. Table 4 presents the parameter estimates and final model designs for each of the measures.

Speech latency—The numeric pattern of the data was similar to that of Experiment 1 with longer initiation times in high attachment than in low attachment. However, this difference was only marginally significant (HA: 2005ms vs. LA: 1913ms, =0.041, SE=0.023, t=1.8). No other effects were significant (codability: =−0.026, SE=0.029, t=−0.9, interaction: =−0.038, SE=0.046, t=−0.8).

Region before the high noun—There were no significant condition effects on the duration of the determiner (*i.e.*, *the*) preceding the high noun (attachment: =−0.000, SE=0.029, t=−0.0, codability: =−0.020, SE=0.118, t=−0.2, interaction: =−0.038, SE=0.058, t=−0.7).

High noun—Consistent with the hierarchical account, the duration of the high noun was significantly longer in the medium codability condition, compared to the high codability condition (Medium: 618ms vs. High: 585ms, =0.107, SE=0.028, t=3.7). There was no effect of attachment (=−0.006, SE=0.023, t=−0.3), nor was there a reliable interaction (=−0.040, SE=0.045, t=−0.9). The absence of an interaction is consistent with the radical version of the hierarchical account.

Regions after the high noun—There were no significant condition effects on the duration of "of the" (attachment: =−0.011, SE=0.025, t=−0.5, codability: =0.043, SE=0.040, t=1.1, interaction: =−0.069, SE=0.050, t=−1.4), or on the duration of the low noun (attachment: =0.035, SE=0.026, t=1.4, codability: =0.011, SE=0.035, t=0.3, interaction: (= −0.048, SE=0.052, t=−0.9). However, the duration of the low noun was numerically longer

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in the high attachment structures than in the low attachment structures (HA: 773ms vs. LA: 727ms), consistent with the pattern observed in Experiment 1.

The duration of the relative clause was significantly predicted by the contrast between the medium and high codability conditions (Medium: 1230ms vs. High: 1085ms, =0.112, SE=0.041, t=2.7). Attachment type was not a reliable predictor of the duration of the relative clause (=−0.006, SE=0.015, t=−0.4), nor was the interaction between attachment and codability (=−0.005, SE=0.029, t=−0.2).

Discussion

The results of Experiment 2 replicated the codability effect at the high noun found in Experiment 1 despite the fact that participants were given less opportunity to prepare their utterance prior to speaking. The duration of the high noun was significantly longer when the relative clause noun was of medium codability than when it was highly codable. Consistent findings across experiments with and without a preview period suggest that the codability effects found in Experiment 1 reflected on-line planning processes, and are not restricted to cases in which speakers engage in extensive preparation prior to speaking.

In Experiment 2, speech onset times were delayed in the high attachment compared to low attachment structures as in Experiment 1, but this effect was only marginally significant. This result adds to the evidence that speakers had prepared at least part of the syntactic structure of the relative clause prior to speaking. In Experiment 1, the effect of attachment on the duration of the low noun was interpreted as reflecting greater planning difficulty in the high attachment structures and the presence of a prosodic break after the low noun. In Experiment 2, although there was no significant effect of attachment on the duration of the low noun, the difference was in the same direction as in Experiment 1.

One important difference in the results of Experiments 1 and 2 is that attachment effects were overall reduced in Experiment 2. While attachment type affected the durations of the preamble, the low noun and the relative clause as well as speech onset latencies in Experiment 1, the attachment effects were restricted to speech onset latencies in Experiment 2. The attenuation of the attachment effect may have been the result of reduced pre-planning in Experiment 2 due to the lack of a preview period. The reduced attachment effect in Experiment 2 might also be due to the difference in the form of the utterance produced across experiments (imperative sentences vs. complex noun phrases). However, a post-hoc analysis conducted on pooled data from both experiments showed that the attachment effect was extended across the sentence: There was a significant effect of attachment type on the low noun length and the relative clause length as well as on speech onset latencies. More crucially, the magnitude of the codability and attachment effects did not vary significantly across experiments, for either the speech latency or the duration measures (see Appendix C for the results of this post-hoc analysis). The results of this post-hoc analysis suggest that caution needs to be taken in drawing strong conclusions about the source of the difference in the results of Experiment 1 and Experiment 2.

General Discussion

Words in an utterance are not simply linearly ordered strings. They also have hierarchical relationships with syntactically and semantically related components organized into higher-level syntactic units (Lashley, 1951; Garrett, 1975; Dell, et al., 2000). As a result of these hierarchical dependencies, linearly adjacent words are not always hierarchically close ones. The words in a syntactic dependency relationship, like a head and its modifier or a head and its argument, are often linearly separated from each other by other intervening words.

According to serial views of the production process (e.g., Bock & Levelt, 1994; Griffin, 2001; Kempen & Hoenkamp, 1987; Levelt, 1989; Martin et al., 2010; Smith & Weeldon, 1999), utterance production occurs incrementally with a chunk of an utterance prepared prior to speech onset and the next part of an utterance prepared during speech. The goal of the present research was to test whether, in *addition to* this incremental preparation, speakers engage in hierarchical planning such that elements of an unfolding utterance in a syntactic dependency relationship are more likely to be planned together. In order to investigate the hierarchical planning hypothesis, we focused on the planning of lexical items and manipulated the hierarchical structure of the sentence while holding linear order constant using the ambiguous relative clause construction.

The linear planning account predicts that incremental planning should largely be constrained by the surface order of the utterance. We contrasted this view with two versions of a hierarchical planning account—moderately and radically hierarchical planning—which both predict that elements in a dependency relationship should be planned together, differing in whether hierarchical planning occurs only when the dependency relationship is direct (moderately hierarchical) or for both direct and indirect dependencies (radically hierarchical). In the relative clause construction used here, the relative clause formed a dependency relationship with the high noun either directly (high attachment) or indirectly (low attachment), while holding surface word order constant. Our findings were consistent with the radical version of the hierarchical planning. The duration of the high noun was longer when the relative clause noun was medium codable than when it was highly codable, suggesting that there was look-ahead planning of the relative clause at the lexical level during the articulation of the high noun. Consistent with the radically hierarchical planning account, this effect did not interact with attachment type, suggesting that the lexical representations of both direct and indirect dependents were planned in advance in the production of the relative clause sentences.

One might argue that the current finding does not rule out a version of the linear account that postulates a wide scope of planning. On such a wide-scope view, the entire sentence would be planned as a large and unstructured domain[2]. By contrast, on the radically hierarchical account, advance planning is grammatically structured, with structurally adjacent elements planned together. While both the radically hierarchical account and the wide-scope account predict extensive advance planning, only the hierarchical account provides a coherent account of our data. First, the wide-scope account fails to explain why the planning of the relative clause was initiated specifically at the high noun in both Experiments 1 and 2 (i.e., the codability effect on the duration of the high noun), and not prior to this region. After all, if speakers planned a large and unstructured unit of content prior to speaking, including the entire relative clause, this planning should consume more time when the final noun was lower in codability, delaying speech onset. However, we found no evidence of this, suggesting that the final noun was not selected prior to speech onset. The fact that this codability effect was delayed until during articulation of the high noun even when participants were provided with plenty of time to prepare the full sentence prior to speaking (Experiment 1) demonstrates that the effects of codability at the high noun are linked to the hierarchical relationship between the noun and the relative clause, as opposed to wide-scope planning of the entire sentence. Moreover, if speakers were simply planning a large and unstructured unit, the extra planning time provided in Experiment 1 should have allowed for lexical selection to take place. Second, a wide-scope account fails to explain why grammatical structure effects were seen in both experiments on speech latency (marginal in Experiment 2). On a wide-scope account, all the elements of the unit would be planned

[2]Note that under the wide-scope view, the planning scope is not structured hierarchically or linearly; if it were, such

together with no influence of grammatical structure. The fact that we do see grammar influencing planning from the earliest moments provides further evidence that advance planning is grammatically defined.

Although our data show that the scope of hierarchical planning can be quite extensive, our data also suggest that there are limits to how far ahead lexical planning can proceed. Codability effects at the high noun suggested that lemmas for all dependents were planned at the point of the head noun. However, we did not find any evidence showing that the lemma for the relative clause noun was planned *before* the articulation of the high noun in Experiment 1 in which speakers produced instructions with the verb (*i.e*., the preamble phrase). This suggests that the scope of lexical selection can be extensive and can include lemmas for both direct and indirect dependents, but lexical retrieval at the verb may be restricted to its direct dependents (*e.g*., Meyer, 1996).

Two differing accounts have been proposed to account for interactions between syntactic and lexical processes in language production. One account argues that speakers engage in early formulation of sentence structures, followed by lexical retrieval processes (*e.g*., Bock, Irwin, & Davidson, 2004; Bock, Irwin, Davidson, & Levelt, 2003). By contrast, the other account argues that sentence formulation is driven by lexical retrieval such that the most accessible element is produced first, which has consequences for the speaker's choice of sentence structures (Bock, 1982; 1986; Bock & Warren, 1985; McDonald, Bock, & Kelly, 1993). We found an effect of attachment type on speech latencies in both experiments. This finding suggests that speakers had begun to build the syntactic structure of the relative clause prior to speaking, which is consistent with the account that assumes a formulation of a structural frame prior to lexical access. Furthermore, the finding that the scope of lexical planning was modulated by the dependency relationships between words provides evidence that different levels of processing interact with each other in language production (see Bock 1987 for a review, but see also Wheeldon et al., 2013, for the absence of an effect of lexical availability on the scope of syntactic planning).

Our findings are consistent with Bock and Cutting (1992)'s analysis of attraction errors (e.g., production of a verb that agrees with an adjacent plural noun when the subject noun is singular). Bock and Cutting find that these errors are more common when the intervening noun, or attractor, is part of a prepositional phrase (e.g., *The editor of the history books are on vacation*.) than when it is part of an embedded clause (e.g., *The editor who rejected the books are on vacation*.). Like our findings, this result suggests that the subject and verb, which are hierarchically proximate, are planned together independent of linear order. However, one limitation of these findings is that it is difficult to determine whether they reflect typical language production, or are limited to situations in which the speaker produces an error. The fact that the present findings show hierarchical planning at the lexical level in perfectly fluent utterances provides converging evidence for hierarchical planning in language production. Further, our findings suggest that the underlying mechanism of hierarchical planning may be involved in both subject-verb agreement and lemma selection.

Taken together, the results of two experiments show that speakers engage in hierarchical planning in language production. Prior to speaking, and during articulation, the form of the spoken utterance revealed evidence of downstream planning, several words in advance. These results suggest that at least in some circumstances, structural dependencies are calculated before speaking begins, and that while words are uttered in a linear fashion, the way in which they are planned and articulated reflects structural dependencies that are non-isomorphic to the surface form. In conjunction with previous findings of a high degree of linearity in lexical preparation (Griffin, 2001; 2003; Griffin & Bock, 2000; Meyer, et al., 1998), and in message formulation (Brown-Schmidt & Konopka, 2008), the present research shows that such lexical incrementality may co-exist with hierarchical planning of certain structurally-dependent lexical items.

Although our data show that speakers engage in hierarchical planning, the structure of advance planning (i.e., hierarchical or linear), and not just its scope (e.g., one word or two) is likely to vary significantly as a function of task demands, availability of the to-be-produced structure (see Konopka, 2012), and speaker-internal characteristics such as working memory (Hartsuiker & Barkhuysen, 2006; Slevc, 2011). The structure of planning may also vary systematically across types of structural dependencies in language. For example, the lemmas for verbs and their arguments and those for some types of modifiers may be planned together regardless of surface structure, but adjuncts and other types of modifiers (e.g., Brown-Schmidt & Konopka, 2008) might be planned more incrementally. Plan-modification theories of body movements (Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007) may offer some insights into how a hierarchical utterance plan interfaces with incremental preparation; in such a view, a hierarchal plan for a movement is continuously adjusted throughout the execution of the plan, rather than separate plans being executed for each component movement.

In the production literature, the notion of word-by-word incremental planning (Griffin, 2001; Brown-Schmidt & Konopka, 2008) has been contrasted with proposals of a clausal planning scope (Garrett, 1975). Such debates about incrementality are essentially about the scope or units of advance planning— for whether it is clausal or lexical, the units of planning under either framework (word or clause) would likely be planned incrementally, one after the other. Our findings that the scope of planning can be broad and grammatically structured suggest that the notion of incrementality based on word-by-word planning needs to be re-evaluated. Given the variable findings across studies, an important future direction for the field of language production is to explore varying scopes of planning and within a given planning scope, what the structure of that planning is. By contrast, the present work was designed to begin to ask questions about the structure of planning—specifically, whether the structure of planning reflects hierarchical dependencies. In showing evidence that lexical planning is mediated by a hierarchical structure involving both direct and indirect dependency relationships, we show that lexical planning of post-nominal modifiers can proceed over a large and grammatically structured domain. The fact that lemmas for the relative clause were planned at the high noun that was in an either direct or indirect dependency relationship with the relative clause suggests that planning can be broad in scope at least in the relative clause construction, and this extensive advance planning is guided by hierarchical relationships from the earliest moments of planning.

In addition to providing insights into the structure of planning in speech production, the present research affirms a methodological tool—the study of word durations—to examining planning. While some previous research has shown that word durations are informative about sound- (Kawamoto et al., 1998) and conceptual-level (Ferreira & Swets, 2002) planning processes, our findings provide further evidence that word durations provide insights into lexical and structural planning. The use of duration measures to examine questions in the psycholinguistics literature follows directly from a history of research on the prosodic form of utterances as a cue to other linguistic structures including syntax (*e.g*., Kjelgaard & Speer, 1999; Marslen-Wilson, Tyler, Warren, Grenier, & Lee, 1992; Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991; Snedeker & Trueswell, 2003; Speer, Kjelgaard, & Dobroth, 1996; Warren, Grabe, & Nolan, 1995) and information structure (e.g., Arnold, 2008; Dahan, Tanenhaus, & Chambers, 2002; Ito & Speer, 2008; Watson, Gunlogson, & Tanenhaus, 2008). Our findings extend this research in suggesting that prosody could also be used as a tool to examine other aspects of language research like the scope of advance planning in language production.

In conclusion, speakers are faced with the challenge of implementing a message into a linearly ordered string of speech sounds. We demonstrate that the mechanisms by which speakers transition from thought to speech are not strictly linear and instead the speaker begins with a structured utterance plan that reflects hierarchical dependencies among the message elements. That such hierarchical dependencies are evident in the surface form of speech shows that this hierarchical structure is preserved even as words are linearized in time. This planning of both hierarchical and linear order may offer insights into the interface of thinking and speaking: While at first blush, the linear order of words is incompatible with the wholistic conceptualization of a message, our findings show that the dependencies contained in a message are never fully lost in the linearization process.

Acknowledgments

We would like to thank Dominique Simmons for assistance with data collection. Duane G. Watson and Eun-Kyung Lee were supported by NIH Grant R01DC008774 and the James S. McDonnell foundation.

Appendix

Appendix A

Mean durations and parameter estimates for each critical region, for both fluent and disfluent trials.

Experiment 1: Mean speech latencies (SE) and mean durations (SE) for each critical region, for both fluent and disfluent trials (225 high attachment and low attachment pairs)

	Latency to speak	Click on the	A	of the	B	(that's) below the C
HA-High	1339 (31)	666 (16)	623 (13)	375 (11)	873 (22)	1053 (16)
HA-Medium	1297 (31)	660 (15)	666 (13)	378 (12)	849 (18)	1197 (23)
LA-High	1231 (24)	620 (12)	628 (16)	362 (9)	769 (19)	996 (16)
LA-Medium	1241 (29)	632 (13)	652 (13)	397 (12)	837 (19)	1190 (26)

Experiment 1: Parameter estimates for speech latency and each critical region, for both fluent and disfluent trials. The models also included by-participant and by-item random intercepts.

		Latency to speak	Click on the	A	of the	B	(that's) below the C
Attachment	β	0.042	0.041	0.009	−0.006	0.074	0.039
	SE	0.022	0.024	0.025	0.030	0.027	0.022
	t	1.9(*)	1.7	0.4	−0.2	2.8*	1.8(*)
Codability	β	−0.017	0.047	0.113	0.033	0.095	0.169
	SE	0.027	0.041	0.040	0.049	0.042	0.066
	t	−0.6	1.1	2.8*	0.7	2.3*	2.6*
Attachment × Codability	β	−0.031	−0.006	0.019	−0.056	−0.096	−0.038
	SE	0.045	0.048	0.050	0.061	0.054	0.044
	t	−0.7	−0.1	0.4	−0.9	−1.8(*)	−0.9
Trial order	β	−0.018	−0.013	−0.009	−0.008	−0.009	−0.007
	SE	0.001	0.001	0.001	0.002	0.001	0.001
	t	−14.3*	−9.5*	−6.5*	−4.9*	−6.4*	−6.1*
N1 log length	β	0.016	0.140	0.087	--	--	--
	SE	0.034	0.049	0.049	--	--	--

Experiment 1: Parameter estimates for speech latency and each critical region, for both fluent and disfluent trials. The models also included by-participant and by-item random intercepts.

		Latency to speak	Click on the	A	of the	B	(that's) below the C
	t	0.5	2.8*	1.8(*)	--	--	--
N1 log frequency	β	−0.034	0.112	0.018	--	--	--
	SE	0.050	0.071	0.070	--	--	--
	t	−0.7	1.6	0.3	--	--	--
N2 log length	β	−0.003	0.020	0.030	0.035	0.316	--
	SE	0.028	0.037	0.037	0.046	0.039	--
	t	−0.1	0.5	0.8	0.8	8.0*	--
N2 log frequency	β	−0.045	−0.017	0.067	−0.010	0.059	--
	SE	0.026	0.032	0.032	0.034	0.030	--
	t	−1.7	−0.5	2.1*	−0.3	2.0*	--
N3 log length	β	0.032	−0.006	−0.035	0.009	0.088	0.235
	SE	0.032	0.040	0.040	0.049	0.043	0.041
	t	1.0	−0.2	−0.9	0.2	2.1*	5.7*
N3 log frequency	β	0.011	0.028	0.037	0.009	0.047	0.018
	SE	0.022	0.029	0.029	0.036	0.031	0.032
	t	0.5	1.0	1.3	0.3	1.5	0.6

Experiment 2: Mean speech latencies (SE) and mean durations (SE) for each critical region, for both fluent and disfluent trials (229 high attachment and low attachment pairs)

	Latency to speak	The	A	of the	B	(that's) below the C
HA-High	2004 (40)	156 (3)	592 (11)	407 (16)	813 (21)	1154 (32)
HA-Medium	1949 (38)	159 (6)	602 (10)	439 (31)	745 (18)	1210 (16)
LA-High	1872 (37)	161 (6)	585 (11)	360 (8)	769 (16)	1091 (13)
LA-Medium	1912 (38)	155 (7)	635 (12)	412 (15)	721 (13)	1276 (24)

Experiment 2: Parameter estimates for speech latency and each critical region, for both fluent and disfluent trials. The models also included by-participant and by-item random intercepts.

		Latency to speak	The	A	of the	B	(that's) below the C
Attachment	β	0.042	−0.006	−0.015	0.009	0.029	−0.006
	SE	0.022	0.029	0.022	0.028	0.026	0.017
	t	1.9(*)	−0.2	−0.7	0.3	1.1	−0.4
Codability	β	0.025	0.023	0.103	0.052	−0.025	0.119
	SE	0.037	0.101	0.027	0.046	0.045	0.042
	t	0.1	0.2	3.8*	1.1	−0.6	2.9*
Attachment × Codability	β	−0.030	−0.032	−0.040	−0.061	−0.024	−0.052
	SE	0.044	0.059	0.043	0.057	0.052	0.035
	t	−0.7	−0.6	−0.9	−1.1	−0.5	−1.5
Trial order	β	−0.011	−0.008	−0.007	−0.007	−0.007	−0.002

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Experiment 2: Parameter estimates for speech latency and each critical region, for both fluent and disfluent trials. The models also included by-participant and by-item random intercepts.

		Latency to speak	The	A	of the	B	(that's) below the C
	SE	0.001	0.002	0.001	0.002	0.001	0.001
	t	−9.3*	−4.8*	−6.4*	−4.7*	−4.9*	−2.2*
	β	−0.013	0.222	−0.005	--	--	--
N1 log length	SE	0.044	0.128	0.032	--	--	--
	t	−0.3	1.7	−0.2	--	--	--
	β	0.141	0.319	0.124	--	--	--
N1 log frequency	SE	0.056	0.128	0.042	--	--	--
	t	2.5*	2.5*	2.9*	--	--	--
	β	0.008	−0.008	0.069	−0.042	0.229	--
N2 log length	SE	0.032	0.056	0.026	0.039	0.037	--
	t	0.2	−1.4	2.7*	−1.1	6.2*	--
	β	0.048	−0.065	0.073	−0.007	−0.042	--
N2 log frequency	SE	0.029	0.045	0.025	0.045	0.031	--
	t	1.7	−1.4	2.9*	−1.2	−1.4	--
	β	0.039	0.010	−0.036	−0.007	−0.014	0.130
N3 log length	SE	0.036	0.064	0.029	0.045	0.043	0.033
	t	1.1	0.2	−1.2	−0.2	−0.3	3.9*
	β	0.016	0.052	0.013	0.028	−0.032	−0.045
N3 log frequency	SE	0.023	0.041	0.019	0.029	0.028	0.021
	t	0.7	1.3	0.7	1.0	−1.2	−2.1*

Appendix B

The Number of disfluent trials by Condition.

Experiment 1: Number of disfluent trials

	HA-High	HA-Medium	LA-High	LA-Medium
Click on the	2	1	2	0
A	1	0	1	0
of the	1	2	0	0
B	2	0	1	0
(that's) below the C	5	2	4	6

Experiment 2: Number of disfluent trials

	HA-High	HA-Medium	LA-High	LA-Medium
The	0	0	0	1
A	0	0	0	1
of the	2	2	0	0
B	1	0	1	0
(that's) below the C	2	1	0	4

Appendix C

Mixed effects models with attachment, codability, experiment, and their interactions as fixed effects. The models also included by-participant and by-item random intercepts.

		Latency to speak	(Click on) The	A	of the	B	(that's) below the C
Attachment	β	0.043	0.023	0.005	−0.013	0.054	−0.055
	SE	0.017	0.019	0.016	0.19	0.019	0.018
	t	2.6*	1.2	0.3	−0.7	2.8*	−3.1*
Codability	β	−0.001	0.023	0.105	0.037	0.046	0.116
	SE	0.025	0.073	0.030	0.039	0.034	0.042
	t	−0.04	0.3	3.5*	1.1	1.3	2.8*
Experiment	β	−0.445	1.438	0.078	0.027	0.11	0.034
	SE	0.088	0.078	0.082	0.079	0.087	0.057
	t	−5.1*	18.5*	1.0	0.3	1.3	0.6
Attachment × Codability	β	−0.022	−0.012	−0.007	−0.062	−0.067	−0.021
	SE	0.034	0.039	0.033	0.038	0.039	0.036
	t	−0.7	−0.3	−0.2	−1.6	−1.7	−0.6
Attachment × Experiment	β	0.007	0.048	0.023	−0.003	0.038	0.062
	SE	0.034	0.039	0.033	0.038	0.039	0.025
	t	0.2	1.3	0.7	−0.1	1.0	2.5*
Codability × Experiment	β	0.026	0.061	0.008	0.001	0.052	0.006
	SE	0.035	0.040	0.034	0.039	0.049	0.026
	t	0.8	1.5	0.2	0.0	1.3	0.3
Attachment × Codability × Experiment	β	0.012	0.033	0.063	0.012	−0.046	0.020
	SE	0.067	0.077	0.066	0.076	0.077	0.050
	t	0.2	0.4	1.0	0.2	−0.6	0.4
Trial order	β	−0.014	−0.010	−0.008	−0.007	−0.008	−0.005
	SE	0.001	0.001	0.001	0.001	0.001	0.001
	t	−15.5*	−9.5*	−8.5*	−6.9*	−7.3*	−6.9*
N1 log length	β	−0.010	0.123	0.039	--	--	--
	SE	0.031	0.093	0.037	--	--	--
	t	−0.3	1.3	1.0	--	--	--
N1 log frequency	β	0.083	0.257	−0.002	--	--	--
	SE	0.041	0.091	0.048	--	--	--
	t	2.0*	2.8*	−0.1	--	--	--
N2 log length	β	−0.013	−0.014	0.044	−0.034	0.288	--
	SE	0.023	0.036	0.025	0.030	0.028	--
	t	−0.6	−0.4	1.8(*)	−1.1	10.1*	--
N2 log frequency	β	0.008	−0.010	0.043	−0.032	0.020	--
	SE	0.021	0.028	0.022	0.024	0.023	--
	t	0.4	−0.4	2.0*	−1.4	0.9	--
N3 log length	β	0.029	0.031	−0.002	−0.007	0.036	0.124

		Latency to speak	(Click on) The	A	of the	B	(that's) below the C
	SE	0.026	0.037	0.027	0.045	0.031	0.023
	t	1.1	0.8	−0.1	−0.2	1.1	5.4*
	β	0.005	0.025	0.019	0.028	0.009	−0.044
N3 log frequency	SE	0.017	0.026	0.018	0.029	0.021	0.016
	t	0.3	0.9	1.1	1.0	0.5	−2.7*

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- The structure of lexical planning was examined using a picture description task.
- Speech onset times and word durations were measured.
- The data show evidence of hierarchical planning for structurally dependent lexical items.

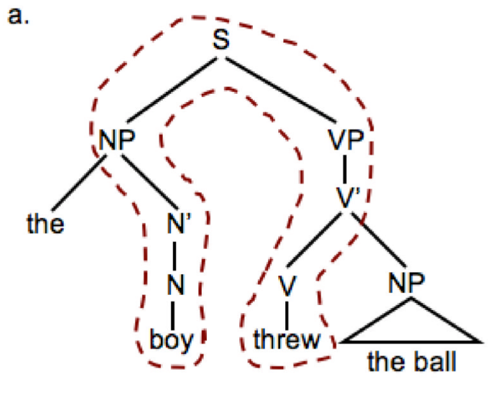

Figure 1.
Tree diagrams for (a) "The boy threw the ball." and (b) "The boy on the left threw the ball".

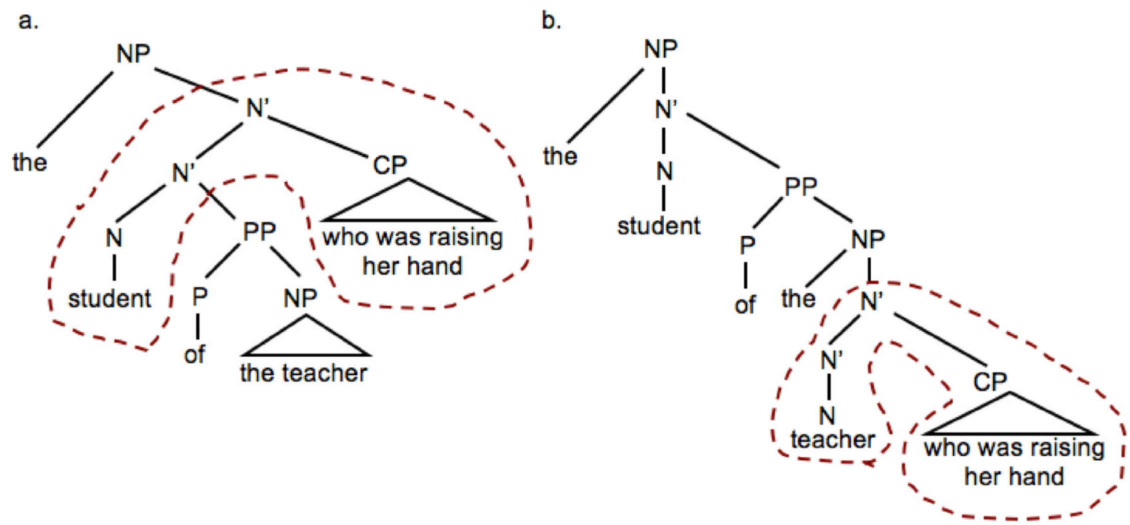

Figure 2.
Tree diagrams for (a) an interpretation in which the relative clause modifies the high noun “student” and (b) an interpretation in which the relative clause modifies the low noun “teacher”. Dashed lines indicate the dependency relationship between the relative clause and its head.

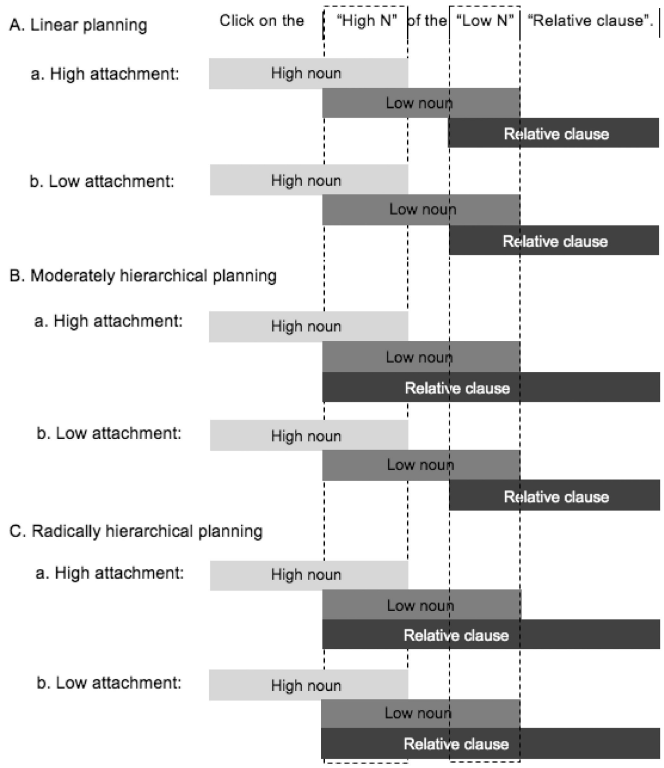

Figure 3.

A schematic diagram showing the predictions of the linear (A), moderately hierarchical (B), and radically hierarchical (C) accounts on the timing of planning lemma representations of relative clauses in high (a) and low (b) attachment conditions. Each bar indicates the timing of selecting lemmas for the high noun, low noun, and relative clause as the utterance proceeds through time.

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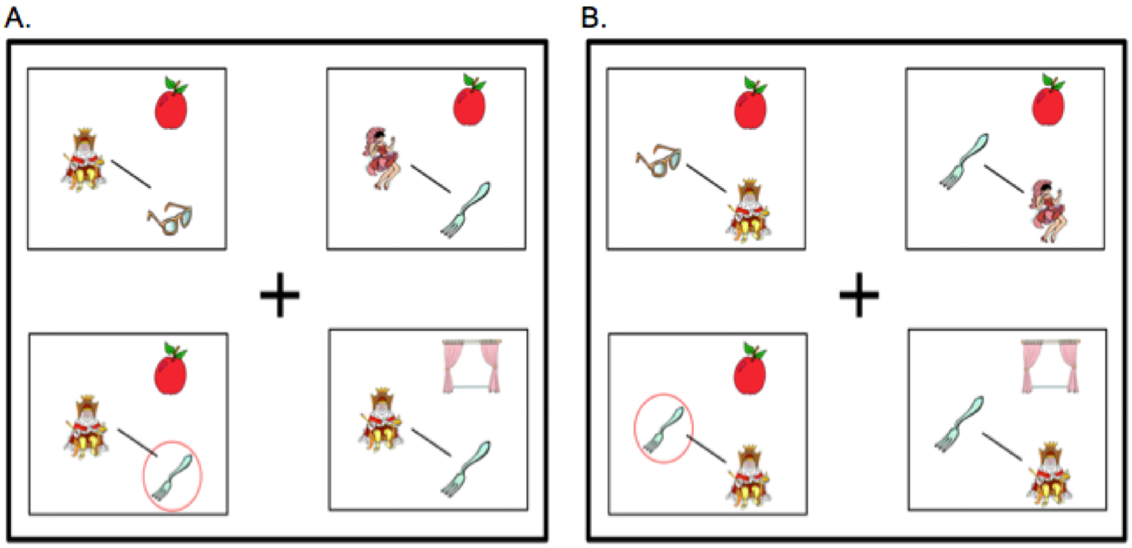

Figure 4. Click on the fork of the king (who's/that's) below the apple

Example displays for (A) the high attachment structure and (B) the low attachment structure in Experiment 1.

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Table 1

Summary of the results from Experiment 1: Mean speech latencies (SE) and mean durations (SE) of each critical region, in msec.

	Latency to speak	***Click on the***	***A***	***of the***	***B***	***(that's) below the C***
HA-High	1345 (32)	668 (17)	610 (13)	361 (9)	839 (20)	1008 (13)
HA-Medium	1311 (32)	647 (14)	661 (14)	354 (7)	831 (19)	1157 (21)
LA-High	1256 (25)	621 (12)	613 (14)	357 (9)	749 (18)	979 (16)
LA-Medium	1252 (32)	618 (14)	642 (14)	388 (13)	819 (18)	1072 (16)

Note. A: high noun, B: low noun. Codability was manipulated for C.

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Table 2

Parameter estimates for speech latency and each critical region in Experiment 1. The models also included by-participant and by-item random intercepts.

		Latency to speak	***Click on the***	***A***	***of the***	***B***	***(that's) below the C***
Attachment	β	0.050	0.049	0.017	−0.014	0.074	0.057
	SE	0.024	0.023	0.024	0.029	0.028	0.019
	t	2.1*	2.2*	0.7	−0.5	2.7*	2.9*
Codability	β	0.003	0.038	0.124	0.017	0.110	0.151
	SE	0.029	0.034	0.034	0.048	0.044	0.061
	t	0.1	1.1	3.7*	0.4	2.5*	2.5*
Attachment × Codability	β	−0.018	0.003	0.024	−0.056	−0.090	0.020
	SE	0.048	0.046	0.049	0.059	0.056	0.039
	t	−0.4	0.1	0.5	−0.9	−1.6	0.5
Trial order	β	−0.018	−0.013	−0.008	−0.008	−0.009	−0.007
	SE	0.001	0.001	0.001	0.002	0.002	0.001
	t	−13.4*	−10.2*	−6.0*	−4.8*	−6.1*	−6.3*
N1 log length	β	0.001	0.086	0.053	--	--	--
	SE	0.036	0.042	0.041	--	--	--
	t	0.4	2.1*	1.3	--	--	--
N1 log frequency	β	−0.033	−0.003	−0.024	--	--	--
	SE	0.053	0.060	0.060	--	--	--
	t	−0.6	−0.01	−0.4	--	--	--
N2 log length	β	0.001	0.036	0.047	0.010	0.314	--
	SE	0.030	0.033	0.033	0.045	0.041	--
	t	−0.0	1.1	1.4	0.2	7.6*	--
N2 log frequency	β	−0.037	−0.035	0.064	−0.036	0.0068	--
	SE	0.027	0.028	0.030	0.033	0.031	--
	t	−1.3	−1.2	2.2*	−1.1	2.2*	--
N3 log length	β	0.040	0.048	0.011	0.034	0.089	0.213
	SE	0.036	0.038	0.039	0.050	0.047	0.040
	t	1.1	1.3	0.3	0.7	1.9(*)	5.3*
N3 log frequency	β	0.021	0.033	0.033	−0.012	0.048	−0.001
	SE	0.023	0.025	0.026	0.034	0.031	0.027
	t	0.9	1.3	1.3	−0.4	1.5	−0.1

Note. A: high noun, B: low noun. Codability was manipulated for C. Statistical significance is indicated by asterisks. Control variables are shaded gray.

Table 3

Summary of the results from Experiment 2: Mean speech latencies (SE) and mean durations (SE) of each critical region, in msec.

	Latency to speak	***The***	***A***	***of the***	***B***	***(that's) below the C***
HA-High	2032 (42)	156 (3)	593 (12)	393 (16)	814 (19)	1085 (12)
HA-Medium	1977 (39)	159 (7)	604 (11)	373 (10)	732 (17)	1213 (17)
LA-High	1877 (39)	161 (6)	576 (11)	355 (8)	741 (15)	1084 (12)
LA-Medium	1949 (39)	155 (5)	631 (13)	410 (16)	712 (14)	1247 (25)

Table 4

Parameter estimates for speech latency and each critical region in Experiment 2. The model for the relative clause region also included by-participant and by-item random intercepts, and by-participant random slopes for codability. The other models included by-participant and by-item random intercepts.

		Latency to speak	***The***	***A***	***of the***	***B***	***(that's) below the C***
	β	0.041	−0.000	−0.006	−0.011	0.035	−0.006
Attachment	*SE*	0.023	0.029	0.023	0.025	0.026	0.015
	t	1.8(*)	−0.0	−0.3	−0.5	1.4	−0.4
	β	−0.026	−0.020	0.107	0.043	0.011	0.112
Codability	*SE*	0.029	0.118	0.028	0.040	0.035	0.041
	t	−0.9	−0.2	3.7*	1.1	0.3	2.7*
	β	−0.038	−0.038	−0.040	−0.069	−0.048	−0.005
Attachment × Codability	*SE*	0.046	0.058	0.045	0.050	0.052	0.029
	t	−0.8	−0.7	−0.9	−1.4	−0.9	−0.2
	β	−0.011	−0.007	−0.007	−0.007	−0.006	−0.003
Trial order	*SE*	0.001	0.002	0.001	0.001	0.001	0.001
	t	−8.8*	−4.5*	−5.9*	−5.0*	−4.4*	−3.5*
	β	0.005	0.105	−0.002	--	--	--
N1 log length	*SE*	0.022	0.095	0.022	--	--	--
	t	0.2	1.1	−0.1	--	--	--
	β	0.158	0.410	0.117	--	--	--
N1 log frequency	*SE*	0.046	0.135	0.045	--	--	--
	t	3.4*	3.0*	2.6*	--	--	--
	β	−0.025	−0.043	0.034	−0.024	0.138	--
N2 log length	*SE*	0.013	0.027	0.013	0.016	0.014	--
	t	−2.0*	−1.6	2.7*	−1.5	9.6*	--
	β	0.025	−0.052	0.075	−0.032	−0.030	--
N2 log frequency	*SE*	0.027	0.045	0.026	0.028	0.026	--
	t	0.9	−1.2	2.9*	−1.1	−1.2	--
	β	0.007	−0.012	−0.012	0.010	−0.004	0.078
N3 log length	*SE*	0.018	0.035	0.018	0.022	0.021	0.016
	t	0.4	−0.3	−0.7	0.5	−0.2	4.8*
	β	0.003	0.015	0.017	0.040	−0.023	−0.052
N3 log frequency	*SE*	0.020	0.040	0.019	0.025	0.023	0.018
	t	0.2	0.4	0.9	1.6	−1.0	−2.8*

Note. A: high noun, B: low noun. Codability was manipulated for C. Statistical significance was indicated by asterisks. Control variables are shaded gray.