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Two sides of the same coin? Comparing structural priming between production and comprehension in choice data and in reaction times

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Abstract

Although structural priming seems to rely on the same mechanisms in production and comprehension, effects are not always consistent between modalities. Methodological differences often result in different data types, namely choice data in production and reaction time data in comprehension. In a structural priming experiment using a maze task with English ditransitives, we collected choice data and reaction time data in both modalities. The choice data showed priming of the double object (DO) and prepositional object (PO) dative. The reaction times revealed priming of the PO dative. In production, PO targets were chosen faster after a PO prime than after a baseline prime. In comprehension, DO targets were read slower after a PO prime than after a baseline prime. This result can be explained from competition between alternatives during structure selection. Priming leads to facilitation of the primed structure or inhibition of the opposite structure depending on the relative frequency of structures, which may differ across modalities.

Keywords

structural priming, maze task paradigm, language production, language comprehension

1. Introduction

When people listen to language, they are confronted with the choices that speakers make with regard to formulating their message. Listeners seem to handle this job by making predictions (Altmann & Kamide, 1999), which implies that they need to adapt when the input does not meet their expectations. These predictions and adaptations are reflected in structural priming effects. Structural priming, which is “the phenomenon by which processing one utterance facilitates processing of another utterance on the basis of a repeated syntactic structure”

(Branigan, 2007, p.1), is often used as a method to investigate mental representations of syntactic structures.

Bock (1986) found that participants who were exposed to a passive prime sentence (e.g., *The building manager was mugged by a gang of teenagers*) were more likely to produce a passive sentence (e.g., *The referee was punched by the fans*) rather than an active sentence (e.g., *The fans punched the referee*) when describing a target picture than when they were presented with an active priming sentence. The structural priming effect has proven to be a robust effect, and it was found with a range of syntactic structures, in multiple languages and with different populations, including children and L2 learners (see Mahowald et al., 2016 for a meta-analysis). Structural priming has also been observed in comprehension (see Tooley & Traxler, 2010 for a review), for instance in self-paced reading, eye-tracking, or fMRI experiments. Arai et al. (2007) measured eye movements during a comprehension experiment with English ditransitives. After reading a prime sentence, which was either a direct object (DO) sentence (e.g., *The assassin will send the dictator the parcel*) or a prepositional object (PO) sentence (e..g, *The assassin will send the parcel to the dictator*), participants listened to DO sentences (e.g., *The pirate will send the princess the necklace*) and PO sentences (e.g., *The pirate will send the necklace to the princess*) while looking at a scene depicting the agent (*the pirate*), recipient (*the princess*), and the object (*the necklace*). Participants looked longer and earlier at the recipient after a DO prime than after a PO prime in the prediction time window (between the onset of the verb and the first object), but only if there was lexical overlap between prime and target.

Structural priming effects have been explained in terms of residual activation of the mental representation of primed structures (Pickering & Branigan, 1998) and/or by error-based implicit learning of meaning-form mappings (Chang et al. 2006). However, it remains unclear whether these mechanisms underlying priming work in the same way in production and in comprehension, as findings from structural priming do not always converge across modalities, as we will discuss in more detail below. Any differences are difficult to interpret though, because production and comprehension paradigms typically rely on different methods and hence types of data (e.g., production choices and reaction times respectively). Different measurement types may lead to differential findings, as Segaert et al. (2011) showed when comparing priming of choices and reaction times in production.

In the current study, we will therefore test a new method to study structural priming in comprehension, namely an adapted version of the maze task paradigm (a variant to self-paced reading in which participants choose between two words at each word of the sentence [Forster, Guerrera & Elliot, 2009]). This paradigm allows us to simultaneously collect reaction times and choice data in comprehension. As such, the maze task paradigm will allow us to disentangle influences from modality and measurement type. We will compare the results of the comprehension experiment to priming effects in a production experiment, in which we also measure choices and reaction times by recording both production choices and onset latencies.

Structural priming across modalities

It has been argued that structural priming in production and in comprehension rely on the same mechanisms (Pickering, McLean & Branigan, 2013; Tooley & Bock, 2014). Tooley and Bock compared priming effects between production (as observed in a sentence repetition task) and comprehension (as measured in a self-paced reading task) by calculating standardized *z*-scores for both modalities and found that the priming effects were of similar magnitude (but note that the sentence repetition task in the production experiment also involves comprehension of the sentence to be repeated and lacks spontaneous production). Some neural evidence for a common mechanism comes from Segaert et al. (2012; 2013), who showed in an fMRI experiment that the same brain areas are involved during structural priming in the different modalities, and that the effects were of the same magnitude in production and in comprehension.

If the mechanisms behind structural priming are indeed the same for comprehension and for production, we may also expect that factors modulating the magnitude of structural priming effects behave similarly in the two modalities. In production, a robust lexical boost effect is observed, meaning that structural priming effects are stronger if the prime and the target contain the same verbs than if different verbs are used between prime and target (Pickering & Branigan, 1998). In addition, structural priming is stronger for less frequent structures than for more frequent structures, which is called the inverse preference effect (Ferreira & Bock, 2006). Hartsuiker et al. (2008) argue that the lexical boost effect, which decays quickly, is due to residual activation (of the stored mental representation) and/or explicit memory of the prime sentence, while long-lasting abstract structural priming is due to an error-based, implicit learning mechanism (Chang et al., 2006). When the parser fails to predict the incoming structure, permanent adaptations are made to the relative weights of structures, making it more likely that the structure is predicted during future processing. The inverse preference effect reflects an error-based implicit learning mechanism, as there is more prediction error and thus more adaptation for less expected structures than for more frequent structures (Ferreira & Bock). More evidence for an implicit learning mechanism causing long-lasting abstract structural priming effects comes from cumulative priming, meaning that structural priming effects persist and accumulate over time (Kaschak, 2007). Moreover, structural priming is modulated by verb bias. Bernolet and Hartsuiker (2010) found that DO priming is stronger for verbs with a preference for the PO structure than for verbs with a DO bias.

Indeed, according to Tooley and Traxler (2018) structural priming in comprehension also involves a short-lived lexical boost effect (due to residual activation and/or explicit memory of the prime sentence) and long-lasting priming effects (due to implicit learning). Nevertheless, whereas findings in production are rather consistent, results have been very variable in comprehension, especially with regard to lexical overlap. Some studies only find priming effects in comprehension in the presence of lexical overlap between prime and target (e.g., Arai et al., 2007; Branigan, Pickering & McLean, 2005; Q. Chen et al., 2013; Tooley, Traxler & Swaab, 2009; Traxler, 2015). Other studies do observe structural priming effects when there is no lexical overlap between prime and target (e.g., Arai & Mazuka, 2014; Giavazzi et al., 2018; X. Chen, Wang & Hartsuiker, 2022; Kim, Carbary & Tanenhaus, 2014; Pickering et al., 2013; Thothathiri & Snedeker, 2008a; Thothathiri & Snedeker, 2008b; Tooley & Bock, 2014; Ziegler & Snedeker, 2019). Importantly, some studies that find structural priming in comprehension both with and without lexical overlap do not find any difference in magnitude, suggesting that structural priming in comprehension is independent of lexical overlap (Fine & Jaeger, 2016; Traxler, 2008). In addition, it has been argued that the lexical boost effect is long-lasting rather than short-lived in comprehension (Pickering et al., 2013; Tooley et al., 2014), whereas Fine and Jaeger (2016) and Tooley and Traxler (2018) find that the lexical boost effect decays during intervening items.

As far as we know, there is no direct evidence yet for an inverse preference effect in comprehension. Many previous comprehension studies focused on the role of lexical overlap due the inconsistencies. The role of implicit learning in comprehension is less well investigated. Still, the inverse preference effect presumably reflects an implicit learning mechanism, and there is evidence pointing towards an implicit learning mechanism in comprehension. Fine and Jaeger (2013) showed that the priming effects as observed in Thothathiri and Snedeker (2008a) were correlated with the prediction error of the prime sentence: priming was stronger after a prime with a higher prediction error than after a prime with a lower prediction error. In addition, X. Chen et al. (2022) found that priming effects for the ditransitive structure in comprehension are modulated by verb bias in a similar way to production. Therefore we may expect that the inverse preference effect will occur in comprehension as well.

In short, although there is evidence that residual activation and implicit learning play a role in structural priming in comprehension as well (through the lexical boost effect and prediction error/verb bias effects respectively), the results in comprehension studies seem to be less consistent than in production. It has been suggested that the results of structural priming experiments in comprehension are much more variable than those in production experiments due to intrinsic differences between production and comprehension (Ziegler & Snedeker, 2019). In comprehension, listeners do not need to build a complete syntactic representation of the sentence, whereas in production, a full representation is always required. As such, priming effects may only be found if the ‘message predictability’ of the target sentences is low enough, so that the listener has to build a full representation of the structure.

Methodological differences

Alternatively, methodological differences may underlie the more variable results in comprehension. The methods to measure structural priming effects in comprehension are less standardized and perhaps also less sensitive than the methods used in production. Whereas structural priming in production is typically investigated by means of a picture description task, there are several techniques used to measure structural priming in comprehension, mainly self-paced reading, eye-tracking, and electroencephalography. Tooley and Traxler (2010) argue that these online methods are less sensitive than the picture description paradigm in production studies, which is an offline measure. Additionally, for structural priming experiments in production, there is a meta-analysis available, which indicates the sample size needed to obtain sufficient statistical power to establish reliable structural priming effects (Mahowald et al., 2016). The desired sample size for structural priming experiments in comprehension is currently unknown. As a result, previous studies differ a lot in terms of statistical power. This makes it complicated to compare results between studies with regard to the lexical boost effect, which is an interaction between priming and lexical overlap. If there is a true interaction between priming and lexical overlap in comprehension as there is in production, potentially underpowered studies may either only find statistical evidence for priming in the strongest category, observing priming in the presence of lexical overlap only (e.g., Arai et al., 2007 [*N* = 64 x 32 items]; Branigan et al., 2005 [*N* = 80 x 24 items]; Q. Chen et al., 2013 [*N* = 36 x 60 items]; Tooley et al., 2009 [*N* = 22 x 80 items /*N* = 44 x 28 items]; Traxler, 2015 [*N* = 104 x 48 items]), or may not be able to observe a statistically significant interaction, reporting equally strong priming both with and without lexical overlap (e.g., Fine & Jaeger, 2016 [*N* = 248 x 40 items]; Traxler, 2008 [*N* = 101 x 40 items]). We do not want to claim that all of these studies are underpowered, but rather that the variability in statistical power may have contributed to the variability in findings.

Measurement types

Importantly, the methodological differences between structural priming experiment in production and comprehension also result in different types of data. Structural priming in production is typically investigated by means of a picture description task. The picture can be described by either of the two alternating structures (e.g., a direct object dative or a prepositional object dative), resulting in (offline) choice data. Structural priming effects in comprehension, on the other hand, are usually measured in terms of online data, such as reaction times. Nevertheless, it is possible to obtain reaction time data in production experiments and choice data in comprehension. For instance, Corley and Scheepers (2002) and Segaert et al. (2011) measured reaction times in addition to choice data in production, whereas Kim et al. (2014) and Giavazzi et al. (2018) collected choice data as well as reaction times in comprehension.

These four studies used a range of methods to obtain both types of data. Corley and Scheepers (2002) investigated the priming of ditransitives in English in a web-based sentence completion experiment. For the prime sentence, participants were asked to complete a given sentence fragment containing a subject, a ditransitive verb, and a noun following the verb, which was either animate to elicit a double object dative (e.g., *the bank manager handed the customer)* or inanimate, in order to elicit a prepositional object dative (e.g., *the bank manager handed the cheque*). The target sentence fragment only included a subject and a ditransitive verb (*the junior surgeon gave*). In addition to the choice data (whether participants produced a double object dative or a prepositional object dative), they also measured the time at which the participant started typing the response. Participants produced more prepositional object datives after a prepositional object prime than after a double object dative, and tended to produce more double object datives after a double object dative prime than after a prepositional object prime. Interestingly, participants also started to produce the target sentence completion significantly earlier in the primed condition. Segaert et al. (2011) obtained similar results with active and passive sentences in a spoken production experiment, measuring the speech onset of the target sentence. Importantly, Segaert et al. found that the inverse preference effect was only found in the choice data. Instead, the onset latencies revealed a ‘preference effect’ here: priming was stronger for the more frequent alternative than for the less frequent alternative. This reemphasizes that differences in priming effects between production and comprehension may be related to the nature of the data collected (e.g., choice vs. latency) rather than modality-related differences per se.

In order to collect choice data in comprehension, Kim et al. (2014) investigated the priming of ambiguously attached prepositional phrases (e.g., *the detective noticed* [*the mirror on the wall*] [*with the crack]/the mirror on* [*the wall with the crack*]). In a self-paced reading task, participants read a non-ambiguous prime with either a high attachment or a low attachment sentence followed by an ambiguous target sentence. Participants were then asked comprehension questions about the target sentence to determine whether they interpreted the sentence with high or low attachment. Sentences were more often interpreted with low attachment after a low attachment prime. The choice data were then used to calculate the priming effects in terms of reaction times. Kim et al. found faster reaction times in the primed situation (i.e., when the interpretation of the target matched the prime condition) than in the unprimed situation (i.e., when the interpretation of the target differed from the prime condition).

In Kim et al.'s (2014) design, structural priming in comprehension cannot be measured with the same syntactic structures as in production if one wants to obtain choice data, as this design requires the target sentence to be ambiguous. In other words, one sentence structure (e.g., one containing an ambiguously attached prepositional phrase) corresponds to multiple scenes (high attachment or low attachment). By contrast, in a picture description task as used for priming in production, one scene (e.g., a transferring action) corresponds to multiple sentence structures (a double object dative or a prepositional object dative). Giavazzi et al. (2018) took a different approach to obtain choice data in comprehension, using non-ambiguous target sentences. They showed participants pictures with a transitive action, for example a penguin painting a dolphin. In an active sentence, *the penguin* is mentioned first, whereas the passive counterpart starts with *the dolphin*. Participants would listen to a sentence either matching the picture (*the penguin paints the dolphin*) or to a sentence with the reversed action (*the dolphin paints the penguin*). Then they had to choose under time pressure whether the picture matched the sentence. As the entities involved always matched between the picture and the sentence, participants needed to make their decision based on the syntactic structure of the sentence. This procedure was the same for prime sentences and for target sentences. For the target sentences, they measured whether participants correctly identified the match or mismatch. In addition, their reaction times were measured. Responses were more accurate and faster in the primed condition than in the unprimed condition. With this paradigm, choice data and reaction times can be collected simultaneously. A potential drawback is that the 'reversed action' is only available with a limited set of syntactic alternations. For instance, in ditransitive sentences such as *the waitress passes the* [*boxer the cake*] / [*the cake to the boxer*], there is no reverse action, since the object is inanimate and the object is animate. As we will explain below, an alternative way to simultaneously collect choice data and reaction times may be to use an adapted version of the maze task paradigm.

The two-stage competition model

The study by Segaert et al. (2011) showed that choice data and reaction times may reveal different priming effects, even within a modality. In the production choice data, they found an effect of inverse preference, that is, stronger priming for the less frequent passive structure. In the reaction time data (i.e., the onset latencies), on the other hand, they found facilitation of the primed active structure. In other words, they found a preference effect: the more frequent active structure was primed more with regard to the onset latencies than the less frequent passive structure.

Segaert et al. (2011) developed the two-stage competition model for structural priming in production in order to explain their paradoxical findings. In this model, grammatical structures are represented as nodes that are associated with a particular activation level. The base level of activation is higher for more frequent structures than for less frequent structures. During the first stage, which is the selection stage, the two alternating structures compete with each other. Semantic and pragmatic factors, but also structural priming, may temporarily affect the activation level of a particular structure. When the activation level of one of the structures reaches the selection threshold, that structure is selected and passed on to the second stage, namely the planning stage.

When the more frequent structure is primed, in the case of Segaert et al. (2011) the active structure, the gap in activation level between the active and the passive structure increases, due to residual activation. As a result, the selection time for the active structure becomes shorter. There is also facilitatory priming during the planning stage. Together, priming of the active structure leads to considerably faster processing of an active sentence after an active prime. By contrast, when the less frequent structure is primed, that is, the passive structure, the activation level of the passive increases, and this decreases the gap in activation level between the active and the passive. Due to increased competition between the active and the passive structure, it takes longer to select a structure after a passive prime. This delay is compensated during the planning stage, which proceeds faster due to priming. This compensation explains why Segaert et al. failed to observe an effect of passive priming on passive sentences. The effect of priming on the competition between structures is illustrated in Figure 1.

[FIGURE 1 ABOUT HERE]

In addition, although Segaert et al. (2011) did not report such an effect, increased competition between structures during the selection stage implies that the prime structure may also affect the reaction times to the opposite alternative. If after a passive prime the parser nevertheless ultimately selects an active structure, it will have taken longer than in unprimed condition to select this active structure due to the increased activation level of the passive structure. This delay will not be cancelled out by compensation during the planning stage, since the selected active structure was not primed. As such, the relative frequency of the alternating structures is crucial in whether priming of a particular structure may lead to facilitation of the primed structure or inhibition effects on the alternative structure during the selection stage.

The selection stage of the two-stage competition model might also account for structural priming in comprehension. Since comprehension lacks a planning stage in which there is faster processing of the primed structure, structural priming effects may be weaker in comprehension than in production (although there may theoretically also be priming during comprehension-specific follow-up processing stages). In addition, as there is no planning stage, the delay due to increased competition after priming with the less frequent structure may not be compensated. Therefore one might even observe negative structural priming effects (i.e., slower processing compared to the baseline condition) in comprehension for the less frequent structure, even though such a negative priming effect might still be compensated by the high prediction error of the less frequent structure (i.e., the inverse preference effect).

In sum, the two-stage competition model predicts different priming effects between choice data and reaction times, as was observed in production by Segaert et al. (2011). Therefore it may be problematic to compare choice data in production to reaction times in comprehension. In addition, although the mechanisms of residual activation and implicit learning underlying structural priming may be the same for production and comprehension at some stage of processing (i.e., the selection stage), as structural priming might also be affected by processing during subsequent, modality-specific stages (i.e., the planning stage during production), structural priming effects may be different between the modalities.

The maze task paradigm

In the current study, we aim to compare the priming effects of ditransitives between production and comprehension in both choice data and in reaction times in order to distinguish modality-specific effects from measurement type effects. We opted for ditransitive structures, because these structures are well-investigated in production and also one of the most investigated structures in comprehension priming studies. Previous methods to simultaneously obtain reaction times and choice data in comprehension cannot be used for ditransitives, as the design of Kim et al. (2014) needs ambiguous target sentences and the paradigm of Giavazzi et al. (2018) requires that the 'reverse' action is available. Therefore we used the maze task paradigm, which was designed as an alternative to self-paced reading (Forster, Guerrera & Elliot, 2009) and which allows to study incremental sentence processing. Similar to self-paced reading, participants read sentences word by word. However, instead of just reading the word and pressing a button in order to proceed, participants complete a forced choice task for each word. For each word of the sentence, participants are presented with a distractor word alongside the correct word (see Figure 2). Participants choose which word will be the continuation of the sentence by pressing a button, and their reaction time is measured. It seems that the effects found in experiments exploiting the maze task are generally larger and have a smaller spillover (i.e., effects on the reaction times of words following the critical word for which effects are predicted) than effects found with self-paced reading (Witzel et al., 2012) and with eye-tracking (Witzel and Forster, 2014). This may partly be due to the constant decision making (requiring a high amount of incremental processing and integration) which is involved in the maze task paradigm but not in self-paced reading, eye-tracking, or EEG. There are different variants of the maze task, according to the type of distractor words used in the task. Distractor words may be pseudowords (lexicality maze), an ungrammatical continuation of the sentence (grammaticality maze), or a statistically unlikely word (automated maze). The latter was developed by Boyce et al. (2020), and it automatically generates distractor words based on a machine-learning language model. It is essentially a variant of the grammaticality maze task, as it uses existing words; often the generated distractor words will be ungrammatical in the context of the critical sentence as well.

[FIGURE 2 ABOUT HERE]

Current study

In our study, we investigated whether the (automated) maze task paradigm is a suitable task to detect structural priming in comprehension. As far as we know, we are the first to exploit the maze task paradigm in a structural priming experiment. The maze task paradigm has many practical advantages over methods such as eye-tracking, EEG, and fMRI, as it is less expensive, requires less materials and is easier to implement in a web-based experiment (cf. Boyce et al., 2020). In addition, it may be more sensitive than self-paced reading and as such, may be able to detect structural priming effects that are hard to find with self-paced reading. Our main reason to use the maze task paradigm, however, was that an adapted version of the maze task allows us to simultaneously collect choice data and reaction time data.

In our comprehension experiment, participants read prime and target sentences. The prime sentences were either DO or PO sentences, or a baseline sentence. We included the baseline condition as a reference level relative to which priming effects are measured (cf. Bernolet et al., 2009), which will allow us to assess the inverse preference effect (i.e., whether the least frequent alternative causes the strongest priming effect). We measured the reaction times to DO and PO target sentences after the different prime conditions. In addition, in the free-choice version, participants chose whether the target sentence they read was a DO or a PO sentence. In order to make a choice between two syntactic alternatives, participants chose between two plausible words, each of which implies a different continuation of the sentence, corresponding to one of the syntactic alternatives. That is, PO datives and DO datives have an identical beginning of the sentence and only start to deviate from each other halfway the sentence (e.g., *The waitress passes the [**boxer** the cake]* (DO) / *[**cake** to the boxer]* (PO)). At the critical point, DO sentences have an animate noun (the recipient), whereas PO sentences mention an inanimate noun (the object). Participants chose between *boxer* and *cake* to determine whether they would read a DO or a PO sentence. For all other words of the sentence, they chose between the correct word and a distractor word.[1]

We expected the participants to more often choose to read a DO target after a DO prime than after a baseline prime, and similarly, that they would more often choose a PO target after a PO prime as compared to a baseline prime. In addition, we expected faster reaction times for a DO target after a DO prime than after a baseline prime and faster reaction times for a PO target after a PO prime than after a baseline prime. Choices may be more sensitive to priming than reaction times. Therefore the effects, if any, may be larger in the choice data than in the reaction time data.

The second aim of our study was to investigate if and how any observed priming effects in comprehension differ from the effects found in production. Corley and Scheepers (2002), Segaert et al. (2011), Kim et al. (2014) and Giavazzi et al. (2018) all suggest that choice data and timing data can both be primed within a modality. That is, the studies find evidence for structural priming with either measure, but they are limited to either production or comprehension. By collecting both choice data and reaction time data in production as well as comprehension, we might be better able to attribute any differences in priming effects (for instance with regard to the lexical boost effect and [inverse] preference effects) between the two modalities to either differences in measurement types or differential processing.

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[1] It may be possible that this choice between two plausible continuations of the sentence draws the attention of participants and reveals the purpose of the experiment. Therefore only half of the participants were assigned to the free-choice version, and we inserted the version (no-choice vs. free-choice) as a fixed effect in our analyses. In none of the analyses there was an interaction between the priming effect and the version. In addition, after the experiment participants were questioned on their thoughts on the purpose of the experiment. The majority of participants thought the experiment was on lexical effects, such as measuring their vocabulary size. Therefore it seems that the choice was not very obvious for participants.

For this purpose, we also tested the critical items of the comprehension experiment in a production experiment. After reading a prime sentence, participants were asked to describe a picture by typing a completion to a sentence prompt. The prompt would include the sentence until the critical point (e.g., *The waitress passes the*). We measured the onset latencies of the critical word, which is the reaction time of the first keystroke (after the prompt). Participants would either write [*boxer the cake*] or [*cake to the boxer*], thus choosing to produce either a DO or a PO sentence.

We hypothesized that the lexical boost effect would be present in both production and comprehension. Any observed priming effects would be stronger if there is verb overlap between prime and target than if the verb of the prime sentence is different from the verb of the target sentence. The two-stage competition model (Segaert et al., 2011) predicts an inverse preference effect in the choice data in both modalities. We thus expected that structural priming effects would be stronger for the less frequent structure than for the more frequent structure. By contrast, the model predicts preference effects in the reaction time data. Overall, priming of reaction times may be weaker in comprehension than in production due to the absence of a planning stage. Consequently, priming of the less frequent alternative might even be negative in comprehension.

Experiment 1: Comprehension experiment

1.1 Method

1.1.1 Participants

For the four different versions of our experiment (with and without a choice between structures in the target sentences, and with and without verb overlap between prime and target), we recruited 96 participants each. In total, we tested 384[2] participants (216 female, 157 male, 11 other) on the online platform Prolific. Participants were aged between 18 and 83[3] (mean: 38.8, SD: 13.9). We recruited participants who had American English as their L1 and did not report any literacy or language problems. They were paid for their participation in the experiment.

1.1.2 Materials and design

We constructed 36 prime-target pairs with ditransitive sentences. We created prime sentences in three prime conditions: a baseline condition, which consisted of an intransitive sentence (e.g., *the monk is laughing*), a double object (DO) dative sentence (e.g., *the waitress passes the boxer the cake*), and a prepositional object (PO) dative sentence (e.g., *the waitress passes the cake to the boxer*). The target sentences came in two variants, namely in the DO condition and in the PO condition.

In addition, we created 144 filler sentences and 4 practice sentences, which were intransitive sentences of the same format as the baseline sentences, and transitive sentences (e.g., *the waitress tickles the dancer*).

For each word of the sentence, participants would need to decide between the correct word and a distractor word (i.e., a word that is an implausible continuation of the sentence).

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[2] If structural priming between production and comprehension is the same, we may expect a similar effect size across modalities. For production, Mahowald et al. (2016) assume a true effect size of .51 (log-odds), and an interaction with lexical overlap with a coefficient of 1. However, we did not a priori exclude the possibility that the effect size is smaller in comprehension. The reported effect size of priming relative to a neutral baseline condition in Traxler (2008) was $d = 0.44$ in the verb-overlap condition and $d = 0.49$ in the condition without lexical overlap (for first-pass regressions in an eye-tracking experiment). Note that Traxler did not observe a significant lexical boost effect, and the effect sizes in for example Arai et al. (2007) were lower (reporting a partial $\eta^2 = 0.20$ in the same-verb condition, and partial $\eta^2 = 0.0015$ in the different-verb condition). For the comprehension experiment, we therefore based ourselves on the more conservative recommendations provided in the Supplementary Materials of Mahowald et al. with an assumed true effect size of .34 and a coefficient of .5 for the interaction with lexical overlap. The estimated power to detect abstract structural priming with 384 participants and 24 critical items (excluding the 12 baseline items) is then between 87% and 94%, and the power to detect an interaction with lexical overlap is between 85% and 88%.

[3] The tested group has a relatively wide age range, which may have led to more variability in the data than in other experiments that are otherwise comparable. We added random intercepts for participants in our statistical models to minimize the impact of interspeaker variability on our statistical results.

For both the prime and the target sentences and for the fillers, we created distractor words using the automated MAZE tool (Boyce et al., 2020), which is available online (https://vboyce.github.io/Maze/). Each sentence started with *The* on the left and *x-x-x* on the right. Other than that, we distributed the correct words and distractor words in such a way that half of the correct words appeared on the left of the screen and half of the correct words appeared on the right of the screen.

We created four different versions. In two versions, the verb of the prime sentence was identical to the verb of the target sentence. In the other two versions, there was no verb overlap between prime and target. In addition, we manipulated whether participants would be able to choose a syntactic structure while reading the target sentences. In the version with a choice, participants had to choose between an animate noun (for a DO sentence) and an inanimate noun (for a PO sentence) on the critical point. To illustrate, for the sentence *The waitress passes the [boxer the cake] / the [cake to the boxer]*, participants in the choice condition had to choose between *boxer* and *cake*. The sentence would then continue as either a DO or a PO, according to their choice. In the version without a choice, participants read a DO target sentence in half of the critical items and a PO target sentence in the other half of critical sentences.

For the two versions (with and without verb overlap) with a choice between DO and PO target sentences, we constructed three lists each, so that every item was preceded by a prime from a different prime condition across the lists. Within each list, we presented the prime sentences equally often in the three priming conditions. For the two versions without a choice, we created six lists each, such that every item appeared as a DO and as a PO after the three prime conditions across the lists. Participants were pseudo-randomly assigned to one of the lists; we tested 96 participants per version. The experiment was programmed in PsychoPy (Peirce et al., 2019) and hosted on its online platform Pavlovia.

1.1.3 Procedure

During the priming experiment, participants would read the prime and target sentences word by word. For each word, two words were presented on the screen: the correct word and the distractor word. To choose the word on the left of the screen, participants needed to press the key A, while they needed to press the key L in order to choose the word on the right of the screen. If they chose the distractor word instead of the correct word, they were prompted to try again, until they chose the correct word. This is different from most previous studies using the MAZE paradigm, where sentences would be cut off after an error. We chose to use the forgiving MAZE paradigm (cf. Boyce et al., 2020), because we wanted to ensure that participants would read the entire prime sentence before reading the target sentence to preserve the balance of the three prime conditions. Immediately after the priming experiment, participants performed the LexTale test, which is a short yes/no-vocabulary test (Lemhöfer & Broersma, 2012) and completed a survey on their demographic background (gender, age, L2 knowledge). A session took about 30 minutes.

1.1.4 Coding

We registered the timing of the key press for the choice of each word. In addition, for the participants assigned to the choice version, we recorded their choice for either the DO or the PO for each target sentence. To calculate the priming effect, we compared the proportion of DO or PO responses after a DO or PO prime respectively to the proportion of DO or PO responses after a baseline prime.

For the analysis of the reaction times, we first removed the outliers for each word, defined as reaction times deviating more than three times the standard deviation from the grand mean. We measured the reaction times for the disambiguating word at the critical point (which is the animate or the inanimate noun) as well as for the words of the spillover area, which is the remainder of the sentence. The spillover area comprised two words for DO sentences (e.g., *The waitress passes the* ***boxer*** *[the cake]*) and three words for PO sentences (e.g., *The waitress passes the* ***cake*** *[to the boxer]*). The reason for this way of measuring priming effects is that structural priming effects in comprehension have been reported in the disambiguating area as well as in the spillover region (e.g., Tooley, 2014; Wei et al., 2016). Since the data are not normally distributed, we log-transformed all the reaction times (log10(x)), after which the Q-Q plot of the plotted reaction times showed a more normal distribution. We calculated the priming effect by comparing the reaction times after a DO or PO prime to the reaction times after a baseline prime.

1.2 Results

1.2.1 Choice data

With regard to the choice data, we collected a total of 6,912 observations. Participants chose to read the PO structure in 3,484 of the cases (50.4%) and the DO structure in 3,428 of the items (49.6%). Figure 3 shows the choice for a DO or a PO structure per prime condition.

[FIGURE 3 ABOUT HERE]

We fitted the responses to a generalized linear mixed model model (R-package lme4, Bates et al., 2015) with a Bobyqa optimizer in order to increase convergeability (Powell, 2009). We ran a model with Prime Condition (baseline/DO/PO) and Verb Overlap (no/yes) and their interaction as fixed factors. The baseline level and no verb overlap served as the reference level. We started with the maximal random effects structure as proposed by Barr et al. (2013), adding random slopes and random intercepts for Participants and Items. At each step, we simplified the model until the model converged without any singularity issues. Following Segaert et al. (2016), we removed random slopes for Item before removing any random slopes for Participants because the variance in items is usually smaller than the variance in participants.

Along the same lines, we first removed the random slope of Verb Overlap before removing the random slope of Prime Condition. The final model included random intercepts for Participants and Items and no random slopes. We calculated the exponentiated estimate using the *summ* function of the *jtools* package (Long, 2022). The model output is summarized in the appendix (Table A1).

The participants chose significantly more often to read a DO after a DO prime in the condition without verb overlap (57.0%) than after a baseline prime (49.2%) ($\beta = -0.35 \pm 0.09$, $p < .001$), indicating facilitatory DO-priming. The condition with verb overlap did not differ significantly from the condition without verb overlap (55.2% DO responses after a DO prime, 50.4% DO responses after a baseline prime), meaning that the priming effect has the same magnitude regardless of verb overlap ($p = 0.26$). As for PO-priming, in the condition without verb overlap between prime and target, there is only a trend towards more PO responses after a PO prime (54.3%) than after a baseline prime (50.8%) ($\beta = 0.16 \pm 0.09$, $p < .1$), but in the condition with verb overlap, there are significantly more PO responses after a PO prime (60.0%) as compared to a baseline prime (49.6%) ($\beta = 0.31 \pm 0.12$, $p < .05$). There is thus lexically-boosted facilitatory priming of the PO structure.

1.2.2 Reaction time data

For the reaction time data, we included a total of 13,824 observations before exclusion of any outliers. Table 1 and Table 2 show the mean reaction times per prime condition for the disambiguating word and each word in the spillover region of the DO and PO target sentences respectively. Figure 4 and 5 plot the reaction times (in ms) per prime condition, separately for the condition with and without verb overlap.

[TABLE 1 ABOUT HERE]

[FIGURE 4 ABOUT HERE]

[TABLE 2 ABOUT HERE]

[FIGURE 5 ABOUT HERE]

We fitted the log-transformed reaction times of each word from the critical point to a linear mixed model (R-package lme4, Bates et al., 2015) with Target Condition (DO/PO), Prime Condition (baseline/DO/PO), Verb Overlap (no/yes), Choice (no-choice/free-choice), and their interactions as its fixed factors. For each fixed effect, the level mentioned first here served as the reference level. We ran separate analyses for the words of the DO targets (6,884 observations) and for PO targets (6,940 observations), since we are interested in the priming effects within each target structure. For each model, we started from the full model with a maximal random effects structure (Barr et al., 2013) and simplified it until convergence. In addition, we removed the non-significant interactions between factors in order to interpret the simple effects. If interactions which are not significant are not removed, this may lead to misinterpretation of the simple effects (Beck & Bliwise, 2014; Cichón, 2020; Engqvist, 2005). Thus, for the models in which the interaction between Prime Condition and Verb Overlap was insignificant, this implies that there was no significant lexical boost effect. The outputs of the final models are reported in the appendix (Table A2-A8).

The DO prime condition did not affect the reaction times to DO targets in the disambiguating word. However, the DO prime condition had a marginal effect on the reaction times to DO targets in the first word of the spillover region in the verb overlap condition. Here, there was a trend towards facilitatory priming of DO targets. That is, we observed faster reaction times to DO targets after a DO prime than after a baseline prime when there was verb overlap between prime and target ($\beta = 0.028 \pm 0.017$, $p < .1$). The DO prime condition did not affect the reaction times to PO targets, relative to the baseline condition.

Turning to the effect of the PO prime condition, we did not find a significant effect of the PO prime structure on reaction times to PO targets in the disambiguating word. In the spillover region, there was a tendency towards faster reaction times to a PO target after a PO prime than after a baseline prime ($\beta = -0.013 \pm 0.008$, $p < .1$). This facilitatory tendency was reversed in the final word of the PO target sentence, where participants were significantly slower after a PO prime than after a baseline prime ($\beta = 0.019 \pm 0.007$, $p < .01$). None of the models to which the reaction times to PO targets were fitted contained a significant interaction between Prime Condition and Verb Overlap.

The PO prime condition also affected the reaction times to DO targets, relative to the baseline prime condition. Regardless of verb overlap, the participants were slower to respond to a DO target after a PO prime than after a baseline prime, which we consider an inhibitory effect of priming. This finding was marginally significant in the disambiguating area ($\beta = 0.018 \pm 0.009$, $p < .1$) and was statistically significant in both the first ($\beta = 0.026 \pm 0.012$, $p < .05$) and the second word of the spillover area ($\beta = 0.017 \pm 0.009$, $p < .05$).

Whether participants had a choice which target structure to read, affected the reaction times to the last word of the target sentence. Participants who chose to read a DO target, had significantly faster reaction times to this last word than participants who were exposed to a DO target in the no-choice version ($\beta = -0.062 \pm 0.022$, $p < .01$). Similarly, participants who chose to read a PO target, were faster to read the final word of the sentence than participants reading a PO target in the no-choice version ($\beta = -0.072 \pm 0.023$, $p < .01$). The choice condition never interacted with any of the priming effects. Reaction times were not affected by verb overlap.

2. Experiment 2: Production experiment

2.1 Method

2.1.1 Participants

We recruited an additional 192[4] participants (117 female, 73 male, 2 other) with American English as their L1 on Prolific. Participants were aged between 18 and 80 (mean: 41.9, SD: 14.7) and did not report any literacy or language problems. They received monetary compensation.

2.1.2 Materials and design

We used the same 36 prime-target pairs with ditransitive sentences and 144 transitive and intransitive fillers as in Experiment 1. Again, we had prime sentences in three prime conditions: a baseline condition, which was an intransitive sentence, a direct object (DO) dative sentence, and a prepositional object (PO) dative sentence.

For each target sentence, we selected a corresponding picture, using the same pictures as in Hartsuiker et al. (2008). In addition, we created a prompt for each target, so that the recorded time of writing onset would be at the critical point. For instance, the prompt could be *The waitress passes the*, which could be completed by *[boxer the cake]* or *[cake to the boxer].* For the transitive fillers, the prompt included the subject and the main verb (e.g., *The waitress tickles* [*the dancer*]). As for the intransitive fillers, only the subject was given (e.g., *The monk [is laughing].*

We added a verification task to the prime sentences. For this purpose, we selected a picture for each prime sentence. Half of the pictures corresponded to the prime sentence, whereas the other half of the pictures did not match the action described by the prime sentences.

We created two versions: one with verb overlap between prime and target, and one without lexical overlap. For both versions, we constructed three lists, so that every item was preceded by a prime from a different prime condition across the lists. Within each list, we

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[4] The estimated power for the production experiment to detect an interaction between the prime structure and the verb overlap condition is, based on the meta-analysis by Mahowald et al. (2016), over 97% (192 participants with 24 critical items, excluding the 12 baseline items).

presented the prime sentences equally often in the three priming conditions. Participants were pseudo-randomly assigned to one of the lists; we tested 96 participants per version. Identical to the comprehension experiment, the production experiment was run using PsychoPy/Pavlovia (Peirce et al., 2019).

2.1.3 Procedure

For each trial of the priming experiment, participants were first presented with the prime sentence. After reading the prime sentence, they would press Space. The prime sentence was then replaced by a verification picture and participants had to decide whether the picture matched the sentence they just read. Then the target picture was shown with the verb written below it. In addition, they would see a text box with the prompt. Participants were asked to write a completion to the sentence.

As in Experiment 1, participants completed the LexTale test and a survey on their demographic background immediately after the priming experiment, which we used to confirm whether participants met the inclusion criteria. A session took about 40 minutes in total.

2.1.4 Coding

We coded the typed responses as a DO dative, a PO dative, or as an Other response. ‘Other’ responses included responses in which only one of the animate entities was mentioned (e.g., *The nun showed the hat*).

We recorded the timing of the first key press, that is, when participants started to type their response. For the analysis of the reaction times, we removed the outliers (reaction times deviating more than three times the standard deviation from the mean). Since the data were not normally distributed, we log-transformed the reaction times (log10(x)). We checked the Q-Q-plot to certify that the log-transformed reaction times had a more normal distribution. We calculated the priming effect by comparing the reaction times after a DO or PO prime to the reaction times after a baseline prime.

2.2 Results

2.2.1 Choice data

We collected a total of 6,912 observations. Participants' responses were coded as a PO dative in 4,590 of the cases (66.4%) and as a DO dative in 2,039 (29.5%) of the cases. We coded 283 responses as Other (4.09%). We excluded the Other responses for further analyses. Figure 6 shows the choice for a DO or a PO structure per prime condition, with and without verb overlap.

[FIGURE 6 ABOUT HERE]

We fitted the responses to a generalized linear mixed model model (R-package lme4, Bates et al., 2015) with a Bobyqa optimizer in order to increase convergeability (Powell, 2009). We ran a model with Prime Condition (baseline/DO/PO), Verb Overlap (no/yes), and their interaction as fixed factors. The baseline level and no verb overlap served as the reference level. We started with the maximal random effects structure as proposed by Barr et al. (2013), adding random slopes and random intercepts for Participants and Items. We simplified the model until it converged without any singularity issues. The final model included random intercepts for Participants and Items and no random slopes. The model output is summarized in the appendix (Table A9).

The significant intercept indicates that participants produced significantly more PO datives than DO datives in the baseline condition ($\beta = 0.79 \pm 0.29$, $p < .01$). After a baseline prime, participants in the condition with verb overlap produced more PO datives than in the condition without verb overlap ($\beta = 1.33 \pm 0.34$, $p < .001$). Participants produced more PO datives after a PO prime than after a baseline prime in the condition without verb overlap ($\beta = 0.28 \pm 0.012$, $p < .05$). The significant interaction between the prime condition and the verb overlap condition showed that this priming effect was even stronger in the condition with verb overlap ($\beta = 1.13 \pm 0.19$, $p < .001$), meaning that we observed lexically-boosted facilitatory PO priming. As for DO-priming, in the condition without verb overlap, participants did not produce more DO datives after a DO prime than after a baseline prime ($p = 0.13$). However, the proportion of DO datives was significantly higher after a DO prime than after a baseline prime in the condition with verb overlap between prime and target ($\beta = -0.47 \pm 0.17$, $p < .01$), indicating lexically dependent facilitatory DO-priming.

2.2.2 Reaction time data

As for the reaction time data, we included a total of 6,568 observations, excluding the 283 Other responses and 39 outliers. Table 3 shows the mean reaction times per prime condition. In Figure 7, the mean reaction times are plotted for both the experiment with and the experiment without overlap.

[TABLE 3 ABOUT HERE]

[FIGURE 7 ABOUT HERE]

We fitted the log-transformed onset latencies to a linear mixed model (R-package lme4, Bates et al., 2015) with Target Condition (DO/PO), Prime Condition (baseline/DO/PO), Verb Overlap (no/yes) and their interactions as its fixed factors. We started from the full model with a maximal random effects structure (Barr et al., 2013) and simplified it until the model converged and had no singularity issues. The final model included random intercepts for Participant and Item and no random slopes. The model output is reported in the appendix (Table A10).

The reaction times were significantly faster for PO sentences than for DO sentences ($\beta = -0.196 \pm 0.028$, $p < .001$). In addition, reaction times to PO target sentences were slower in the condition with verb overlap than in the condition without verb overlap ($\beta = 0.103 \pm 0.041$, $p <$

.05). Most importantly, participants reacted significantly faster to a PO target sentence after a PO prime than after a baseline prime when there was verb overlap between prime and target ($\beta = -0.118 \pm 0.059$, $p < .05$), showing a lexically dependent facilitatory priming effect of the PO structure. The DO prime structure did not have a significant effect on the reaction times of PO or DO targets.

3. Discussion

In the comprehension experiment, participants chose significantly more often to read a DO structure after a DO prime than after a baseline prime, and this facilitatory effect was not affected by lexical overlap between prime and target. In contrast, the facilitatory priming effect of PO priming was only significant if there was lexical overlap between prime and target. As for the reaction times, we did not find an effect of DO primes on either DO targets or PO targets. However, we found that participants responded significantly slower to a DO target after a PO prime sentence than after a baseline prime sentence, regardless of lexical overlap, meaning that there was inhibition of the PO prime structure on DO targets. In addition, we found a facilitatory effect of PO primes on PO targets that was marginally significant, as participants tended to be faster to process a PO target after a PO prime sentence than after a baseline prime sentence, independently of verb overlap. In the production experiment, we observed a slightly different pattern. Participants produced more PO sentences after a PO prime than after a baseline prime, and this facilitatory priming effect was stronger if there was lexical overlap between prime and target. Participants also used a DO sentence more often after a DO prime than after a baseline prime (i.e., facilitatory DO-priming), but only in the lexical overlap condition. In the reaction time data, we found that participants were faster to start producing their PO sentences after a PO prime than after a baseline prime, indicating facilitatory PO-priming but only if there was verb overlap between prime and target. The findings are summarized in Table 4.

[TABLE 4 ABOUT HERE]

With regard to our first research question, our study demonstrates that the maze task paradigm is able to detect structural priming effects in comprehension. In addition, providing participants with a choice between the two alternatives does not significantly affect the results compared to a design in which participants read a particular structure for each target item. Therefore, the maze task seems to be a suitable paradigm to collect choice data and reaction times simultaneously in a structural priming experiment. We also found some evidence for the lexical boost effect, given that PO-priming was only found in the presence of lexical overlap between prime and target. This shows that the maze task is not only able to detect structural priming, but is also sensitive enough to detect certain interactions (such as lexical overlap) with the priming effect.

Our second research question was to what extent these priming effects in comprehension are similar to priming effects in production. For this purpose, we distinguished between measurement type (choice data vs. reaction times) and modality (production vs. comprehension). Although we do not find significant effects in all conditions, we do find evidence for structural priming effects in the choice data as well as in the reaction time data in both modalities, and these structural priming effects can be lexically boosted in both production and comprehension.

More specifically, in the choice data, we found lexically mediated priming of both the DO and the PO structure in production and in comprehension. In production, the lexical boost effect could directly be observed in the PO condition: there was significant PO priming in the condition without lexical overlap, and priming was significantly stronger in the condition with lexical overlap. Although there was no direct evidence for the lexical boost effect in the comprehension data, it can still be inferred that the effect occurs. In the DO condition, there was a significant priming effect in the absence of lexical overlap, suggesting that lexical overlap is not a prerequisite to find structural priming. In the PO condition, priming was only significant in the presence of lexical overlap, suggesting that priming is detected more easily when there is lexical overlap between prime and target. Together, these results suggest that there is abstract structural priming in comprehension which can be magnified by the lexical boost effect. Still, as we only found indirect evidence for lexically-boosted priming in comprehension despite a large number of observations and presumably sufficient statistical power, it seems to be the case that the lexical boost is weaker in comprehension in production. This finding suggests that differences between production and comprehension cannot solely be attributed to additional priming during the planning stage that is specific to production (following from the two-stage model by Segaert et al., 2011), as the lexical boost effect presumably occurs during the selection stage. Instead, it seems that there is less residual activation in comprehension than in production. This may be due to good-enough processing in comprehension, that is, the lack of the need to build a full representation (Ziegler & Snedeker, 2019). As a result, the representation of the prime structure may receive less activation in comprehension than in production, leading to weaker residual activation, which is one component of the lexical boost effect.

As for the inverse preference effect, we expected to observe stronger priming of choices for the less frequent structure than for the more frequent structure in both production and comprehension. Indeed, we do not observe both DO-priming and PO-priming in all conditions, implying that priming may be stronger for one structure than for the other. Crucially, we find different production preferences between production and comprehension. In the production choice data, there is an overall preference for the PO structure (similar to other production studies with L1 speakers of English, e.g., Pickering & Branigan, 1998; Corley & Scheepers, 2002). In the comprehension choice data, there is no clear preference for either the DO or the

PO structure. This means that even if the mechanism responsible for the inverse preference effect (namely prediction error driving implicit learning) is present in both production and comprehension, one may not expect similar outcomes between production and comprehension. Since we observed an equal distribution between the DO and the PO structure, there may be no inverse preference effect in comprehension. Unexpectedly, we also do not find direct evidence for the inverse preference effect in production choices. Despite the PO preference, predicting stronger priming for the DO than for the PO structure, we actually find larger effect sizes (the β coefficients) for PO priming than for DO priming. The strong preference for the PO structure in production may not reflect the relative weights or baseline activation levels of the ditransitive structures, but may instead be due to the target pictures depicting the ditransitive action. In these pictures, the object is always in between the agent and the recipient, reflecting the linear order of the PO structure. At the same time, participants may have chosen more often for the DO structure in the comprehension experiment, as the choice concerned a choice between an animate and an inanimate noun, and animate nouns may be conceptually more accessible than inanimate nouns (cf. Bock & Warren, 1985). Consequently, this accessibility differences might have enhanced the choice for the DO structure. This explanation can account for the absence of an inverse preference effect in production as well as the difference in production preferences between production and comprehension. In other words, the absence of the inverse preference effect in the choice data cannot be explained from a structural priming account such as the implicit learning account or the two-stage competition model, but rather seems to be due to task effects.

The reaction time data, however, do suggest that the relative frequencies of the DO and the PO structure modulated the structural priming effects, although the effect is not an inverse preference effect. In production, we only find facilitatory priming for the more frequent PO structure, which is a preference effect, while in comprehension, we observe an inhibitory effect of PO primes on DO targets. The different findings between production and comprehension may be explained by the two-stage competition model by Segaert et al. (2011). According to this model, there is competition between the structural alternatives during selection of the structural alternative. When the more frequent structure is primed, this will decrease the competition, leading to faster reaction times. When the less frequent structure is primed, the competition between structures will be increased, which leads to slower reaction times.

The reaction time data of the production experiment are in accordance with the onset latencies observed in production by Segaert et al. (2011). We found that participants start producing a PO target response faster after a PO prime than after a baseline prime. We do not find any priming effects for the DO structure. As the PO structure is the most frequent structure in production, there is facilitation both during the selection stage and the planning stage. The lack of priming of the DO structure is caused by inhibition as the result of priming of the least frequent structure during the selection stage, which is compensated during the planning stage. Note that we only find PO priming if there is lexical overlap between prime and target. Segaert et al. did not find an interaction with lexical overlap for the onset latencies; they only found a lexical boost effect in their choice data (but they tested fewer participants than we did, and measured the onset latencies in spoken production instead of written production). Our data show that the onset latencies are sensitive towards verb overlap as well.

As for the reaction time data of the comprehension experiment, we observed that participants are slower to respond to a DO target after a PO prime. This may be due to inhibition caused by the preceding PO prime structure, suggesting that during the comprehension experiment, the PO structure had a lower activation level than the DO structure due to the accessibility of animate nouns, favoring the DO structure (although the DO and the PO structure were chosen equally often in the choice data). Crucially, in Segaert et al. (2011), no direct evidence of longer selection times for the less frequent structure was found, and they argue that this is because of compensation during the planning stage, which proceeds faster for the primed structure. In comprehension, there is no planning stage, and consequently, no compensation for the inhibitory effect (although priming may occur during follow-up processes that are specific to comprehension, such as thematic role mapping). Indeed, we seem to find direct evidence for a longer selection time for a DO target after a PO prime. As such, in the reaction times of the comprehension experiment, we did not find a facilitatory effect caused by priming with the structure with the highest activation level, but we observed an inhibitory effect caused by priming with the structure with the lowest activation level.

It is important to note that the competition model of Segaert et al. (2011) is a model for sentence production and not for sentence comprehension. Nevertheless, the selection stage of the model is congruent with constraint-based models of sentence processing (e.g., MacDonald, Pearlmutter & Seidenberg, 1994; cf. Humphreys and Gennari; 2014 for neuroimaging evidence). Constraint-based models assume that competition between alternatives occurs in order to resolve syntactic ambiguity. Alternatively, the inhibitory effect of the PO prime on the DO target may be explained by garden path theories (e.g., Frazier, 1979; Pickering et al., 2000), which assume that syntactic ambiguity is resolved by reanalysis. These theories assume that one starts with processing the 'default structure', and when the input does not match the expected structure, reanalysis needs to take place in order to process the alternative structure. In this case, one may expect longer processing of the less expected structure. Presumably, this effect is strongest for the least frequent structure after priming of the most frequent structure.

4. Conclusion

Our results suggest that it is fruitful to simultaneously collect choice data and reaction time data in production as well as comprehension, in order to compare the two modalities using more equal measurement types. In both modalities, priming of a particular structure led to an increase in the preference for that structure compared to a baseline reference level. We found evidence that the priming effects were sensitive to the lexical boost effect, but failed to observe an inverse preference effect in the choice data in both production and comprehension. In the reaction time data, we observed facilitated processing of a primed structure in production, but inhibited processing of the alternative structure after priming of a structure in comprehension.

Although the priming effects may differ between modalities, the results for both production and comprehension may be explained from the two-stage competition model of Segaert et al. (2011), in which there is competition between alternatives during the selection stage. The relative frequency of structures determines whether priming leads to facilitated processing of the primed structure or rather inhibition of the opposite structure. Inhibition effects are more likely to be observed in comprehension than in production, because in production, facilitated processing of the primed structure during the planning stage compensates for the inhibition during the selection stage. Thus, our results suggest that that while observed priming effects may be different between modalities, the results may still derive from a similar underlying mechanism of structural priming.

A better understanding of the relationship between priming in production and in comprehension may aid future studies on the nature of structural representations across modalities in children, L2 speakers or people with language problems such as aphasia, for whom participating in a comprehension experiment may be more feasible than in a production experiment. More research is needed to gain a better understanding of how relative frequency interacts with the direction (i.e., facilitation or inhibition) and the magnitude (i.e., (inverse) preference effects) of structural priming effects. Future studies should investigate priming effects in comprehension with structures displaying a larger difference in their relative frequencies to further assess the role of facilitation and inhibition during the processing of primed structures. Our study shows that the maze task paradigm may be a valuable tool to investigate such structural priming effects in comprehension.

Materials, data, and analyses are available online:

[https://osf.io/c6uyz/?view_only=62c937654b1b4133ba20619652ede266]

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Appendix: Statistical models

Table A1. Model output for choice data in comprehension (N = 6912 , log-likelihood = -4543.6).

*glmer(TargetCondition~PrimeCondition*VerbOverlap+ (1|Participant) + (1 |TargetItem))*

	Coefficient	exp(Estimate)	*SE*	Wald's *Z*	*p*-value
(Intercept)	0.03	1.03	0.12	0.25	0.80
PrimeCondition(DO)	-0.35	0.71	0.09	-3.96	<.001***
PrimeCondition(PO)	0.16	1.17	0.09	1.81	<.1.
VerbOverlap(yes)	-0.06	0.95	0.11	-0.51	0.61
PrimeCondition(DO)* VerbOverlap(yes)	0.14	1.15	0.12	1.12	0.26
PrimeCondition(PO)* VerbOverlap(yes)	0.31	1.36	0.12	2.48	<.05*

Table A2. Model output for reaction times to DO targets in comprehension (disambiguating word, N = 6,774).

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + (1|Participant) + (1|TargetItem))

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.750	0.026	306.900	263.242	<.001***
PrimeCondition(DO)	0.000	0.009	6367.000	0.019	0.985
PrimeCondition(PO)	0.018	0.009	6367.000	1.906	<.1.

VerbOverlap(yes)	0.001	0.025	373.700	0.034	0.973
Choice(free-choice)	0.003	0.025	374.800	0.109	0.913

Table A3. Model output for reaction times to DO targets in comprehension (spillover word 1, N = 6,877).

*lmer(log(RT) ~ PrimeCondition*VerbOverlap+MazeChoice* + *(1|Participant)* + *(1|TargetItem))*

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.526	0.025	221.400	256.730	<.001***
PrimeCondition(DO)	0.007	0.012	6470.000	0.594	0.553
PrimeCondition(PO)	0.026	0.012	6468.000	2.095	<.05*
VerbOverlap(yes)	0.020	0.025	536.200	0.820	0.413
Choice(free-choice)	0.035	0.023	378.600	1.539	0.125
PrimeCondition(DO)* VerbOverlap(yes)	-0.028	0.017	6473.000	-1.666	<.1.
PrimeCondition(PO)* VerbOverlap(yes)	0.001	0.018	6473.000	0.050	0.960

Table A4. Model output for reaction times to DO targets in comprehension (spillover word 2, N = 6,803).

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + *(1|Participant)* + *(1|TargetItem))*

	Estimate	*SE*	df	*t*-value	*p*-value

(Intercept)	6.647	0.023	243.200	283.185	<.001***
PrimeCondition(DO)	0.006	0.008	6401.000	0.729	0.466
PrimeCondition(PO)	0.017	0.008	6400.000	2.092	<.05*
VerbOverlap(yes)	0.024	0.022	379.000	1.099	0.272
Choice(free-choice)	-0.062	0.022	380.100	-2.801	<.01**

Table A5. Model output for reaction times to PO targets in comprehension (disambiguating word, N = 6,824)

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + (1 |participant) + (1|TargetItem))

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.712	0.025	343.700	272.787	<.001***
PrimeCondition(DO)	0.002	0.009	6423.000	0.217	0.828
PrimeCondition(PO)	-0.001	0.009	6422.000	-0.131	0.896
VerbOverlap(yes)	0.004	0.025	378.100	0.151	0.880
Choice(free-choice)	0.035	0.025	379.200	1.328	0.154

Table A6. Model output for reaction times to PO targets in comprehension (spillover word 1, N = 6,935).

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + (1|Participant) + (1|TargetItem))

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.478	0.022	271.700	288.773	<.001***

PrimeCondition(DO)	-0.001	0.008	6532.000	-0.079	0.937
PrimeCondition(PO)	-0.013	0.008	6532.000	-1.732	<.1.
VerbOverlap(yes)	-0.005	0.022	380.000	-0.217	0.829
Choice(free-choice)	0.003	0.022	381.100	0.130	0.897

Table A7. Model output for reaction times to PO targets in comprehension (spillover word 2, N = 6,911).

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + (1|Participant) + (1|TargetItem))

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.489	0.021	343.400	313.474	<.001***
PrimeCondition(DO)	0.002	0.007	6508.000	0.307	0.759
PrimeCondition(PO)	0.009	0.007	6508.000	1.348	0.178
VerbOverlap(yes)	0.000	0.021	381.000	-0.010	0.992
Choice(free-choice)	-0.024	0.021	381.900	-1.147	0.252

Table A8. Model output for reaction times to PO targets in comprehension (spillover word 3, N = 6,841).

lmer(log(RT) ~ PrimeCondition+VerbOverlap+MazeChoice + (1|Participant) + (1|TargetItem))

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	6.645	0.025	211.500	265.021	<.001***
PrimeCondition(DO)	0.005	0.007	6435.000	0.632	0.527

PrimeCondition(PO)	0.019	0.007	6435.000	2.718	<.01**
VerbOverlap(yes)	0.025	0.023	380.000	1.102	0.271
Choice(free-choice)	-0.072	0.023	380.900	-3.125	<.01**

Table A9. Model output for choice data in production (N = 6629 , log-likelihood = -2665.0).

*glmer(TargetCondition~PrimeCondition*VerbOverlap+ (1|Participant) + (1 |TargetItem))*

	Coefficient	Exp. estimate	*SE*	Wald's *Z*	*p*-value
(Intercept)	0.79	2.21	0.2875	2.754	<.01**
PrimeCondition(DO)	-0.17	0.84	0.1156	-1.505	0.13
PrimeCondition(PO)	0.28	1.32	0.1171	2.381	<.05*
VerbOverlap(yes)	1.33	3.79	0.3377	3.949	<.001***
PrimeCondition(DO)* VerbOverlap(yes)	-0.47	0.63	0.1718	-2.724	<.01**
PrimeCondition(PO)* VerbOverlap(yes)	1.13	3.10	0.1900	5.958	<.001***

Table A10. Model output for onset latencies in production (N = 6,590).

*lmer(log(RT) ~ target_cond*PrimeCondition*VerbOverlap + (1|Participant) + (1|TargetItem))*

	Estimate	*SE*	df	*t*-value	*p*-value
(Intercept)	8.155	0.050	206.700	164.266	<.001***
TargetCondition(PO)	-0.196	0.028	6498.000	-7.029	<.001***
PrimeCondition(DO)	0.002	0.027	6363.000	0.063	0.950
PrimeCondition(PO)	0.001	0.028	6360.000	0.031	0.975
VerbOverlap(yes)	-0.013	0.059	371.800	-0.211	0.833

TargetCondition(PO)* PrimeCondition(DO)	-0.011	0.035	6365.000	-0.309	0.757
TargetCondition(PO)* PrimeCondition(PO)	0.024	0.036	6363.000	0.684	0.494
TargetCondition(PO)* VerbOverlap(yes)	0.103	0.041	6474.000	2.487	<.05*
PrimeCondition(DO)* VerbOverlap(yes)	0.014	0.043	6365.000	0.331	0.740
PrimeCondition(PO)* VerbOverlap(yes)	0.075	0.051	6369.000	1.467	0.143
TargetCondition(PO)* PrimeCondition(DO)* VerbOverlap(yes)	0.037	0.052	6366.000	0.705	0.481
TargetCondition(PO)* PrimeCondition(PO)* VerbOverlap(yes)	-0.118	0.059	6370.000	-2.000	<.05*

Tables

Table 1. Mean reaction times (in ms) of DO targets per prime condition.

Prime Condition	Disambiguating word	Spillover word 1	Spillover word 2
BASE	919 (394)	754 (351)	794 (262)
DO	917 (378)	744 (324)	800 (263)
PO	933 (388)	767 (328)	813 (269)

Note: standard deviations in parentheses.

Table 2. Mean reaction times (in ms) of PO targets per prime condition.

Prime Condition	Disambiguating word	Spillover word 1	Spillover word 2	Spillover word 3
BASE	902 (379)	689 (264)	683 (217)	788 (262)
DO	903 (379)	688 (270)	685 (218)	797 (271)
PO	899 (367)	675 (254)	684 (209)	803 (267)

Note: standard deviations in parentheses.

Table 3. Mean onset latencies per prime and target condition (in ms)

Target Condition	**DO target**	**PO target**
BASE	3989 (2459)	3485 (2474)
DO	4095 (2705)	3565 (2563)
PO	4074 (2566)	3506 (2.410)

Note: Standard deviations between brackets

Table 4. Summary of findings.

Effect of prime structure on target		Comprehension (experiment 1)		Production (experiment 2)	
		No verb overlap	*Verb overlap*	*No verb overlap*	*Verb overlap*
DO prime	*Choice data*	Facilitation of DO targets		-	Facilitation of DO targets
	Reaction times	-	Facilitation trend of DO targets in spillover	-	
PO prime	*Choice data*	Facilitation trend of PO targets	Facilitation of PO targets	Facilitation of PO targets	Stronger facilitation of PO targets
	Reaction times	Inhibition of DO targets (trend in disambiguation region, significant in spillover)		-	Facilitation of PO targets

Figures

Figure 1.

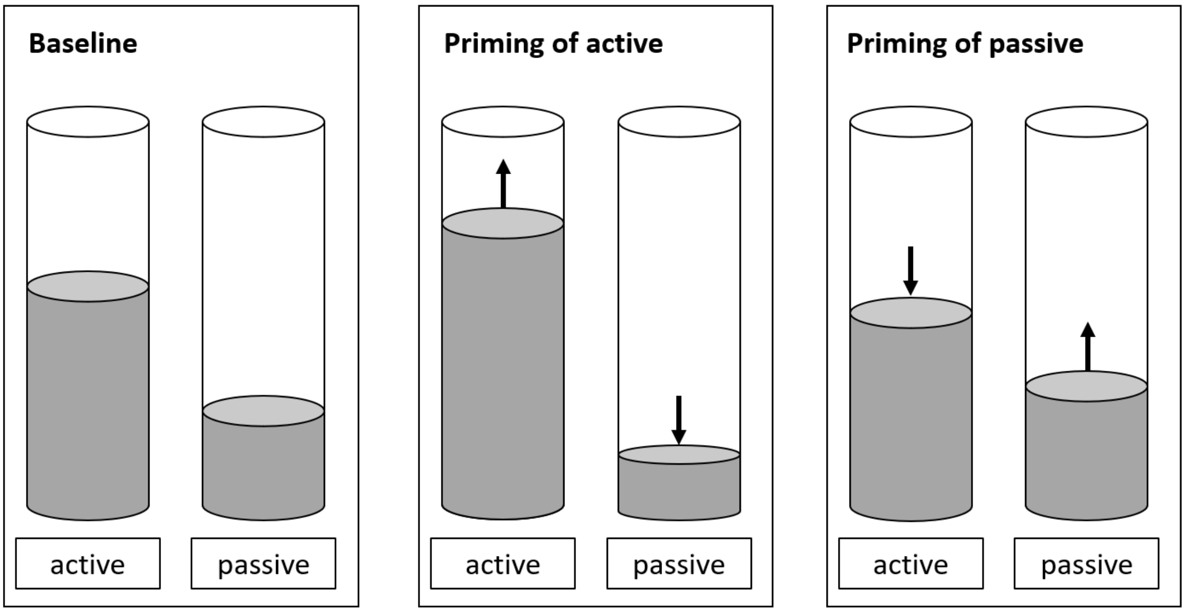

Figure 2.

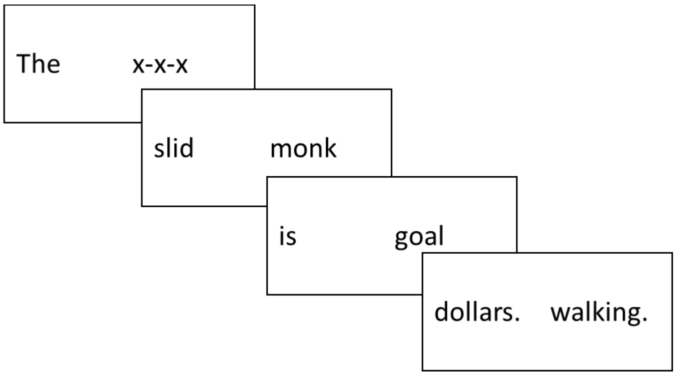

Figure 3.

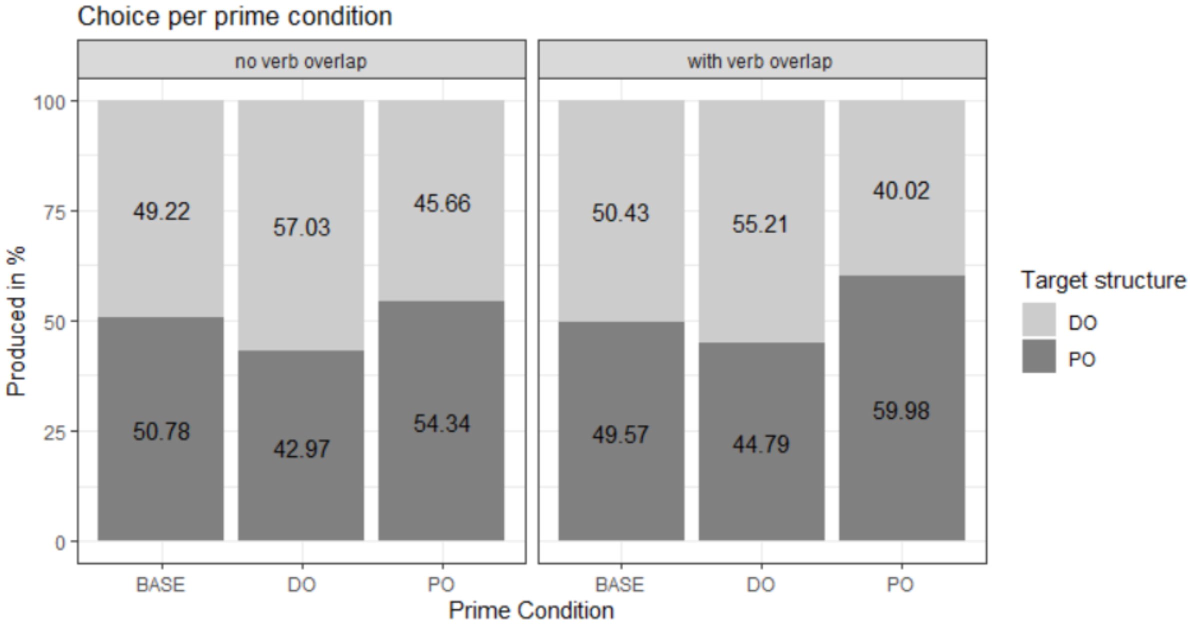
Choice per prime condition
no verb overlap
with verb overlap
Produced in %
100
75
50
25
0
49.22
57.03
45.66
50.78
42.97
54.34
50.43
55.21
40.02
49.57
44.79
59.98
BASE
DO
PO
BASE
DO
PO
Prime Condition
Target structure
DO
PO

Figure 4.

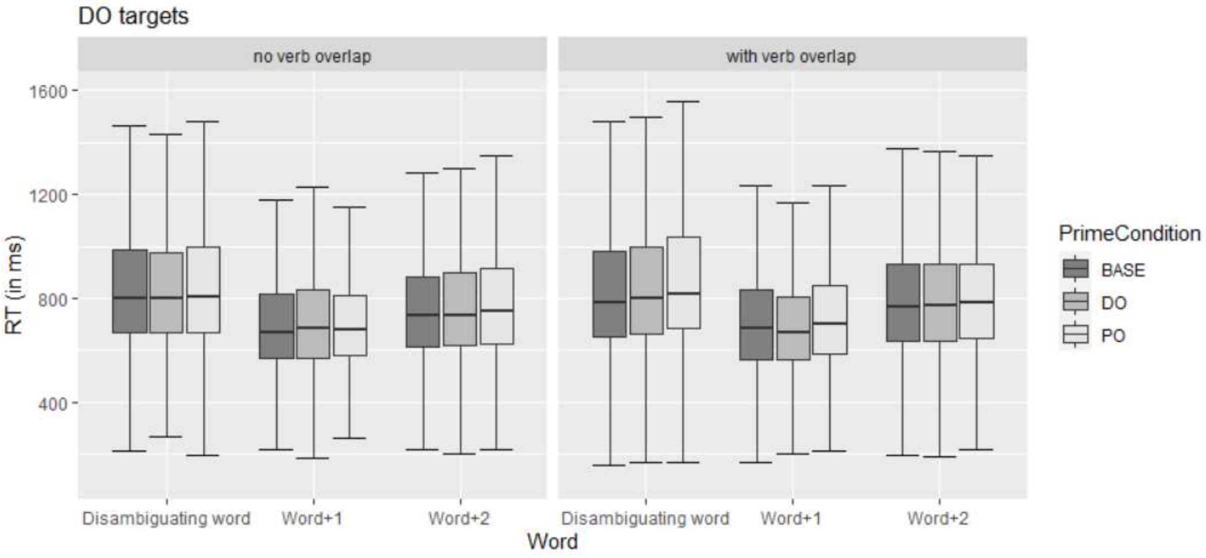
DO targets
no verb overlap
with verb overlap
1600
1200
800
400
RT (in ms)
Disambiguating word
Word+1
Word+2
Disambiguating word
Word+1
Word+2
Word
PrimeCondition
BASE
DO
PO

Figure 5.

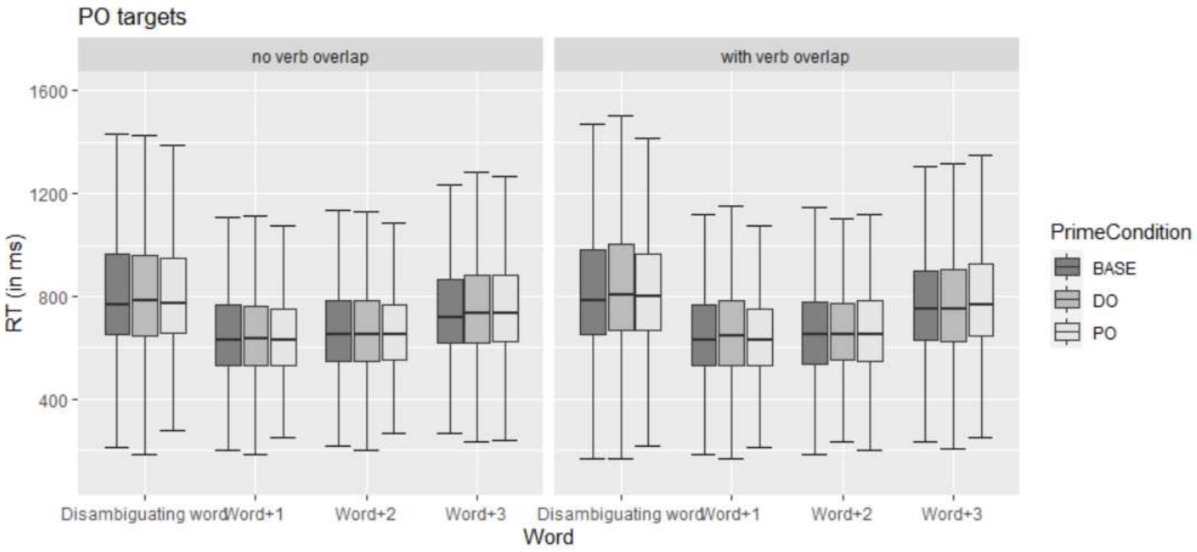
PO targets
no verb overlap
with verb overlap
1600
1200
800
400
RT (in ms)
Disambiguating word
Word+1
Word+2
Word+3
Word
PrimeCondition
BASE
DO
PO

Figure 6.

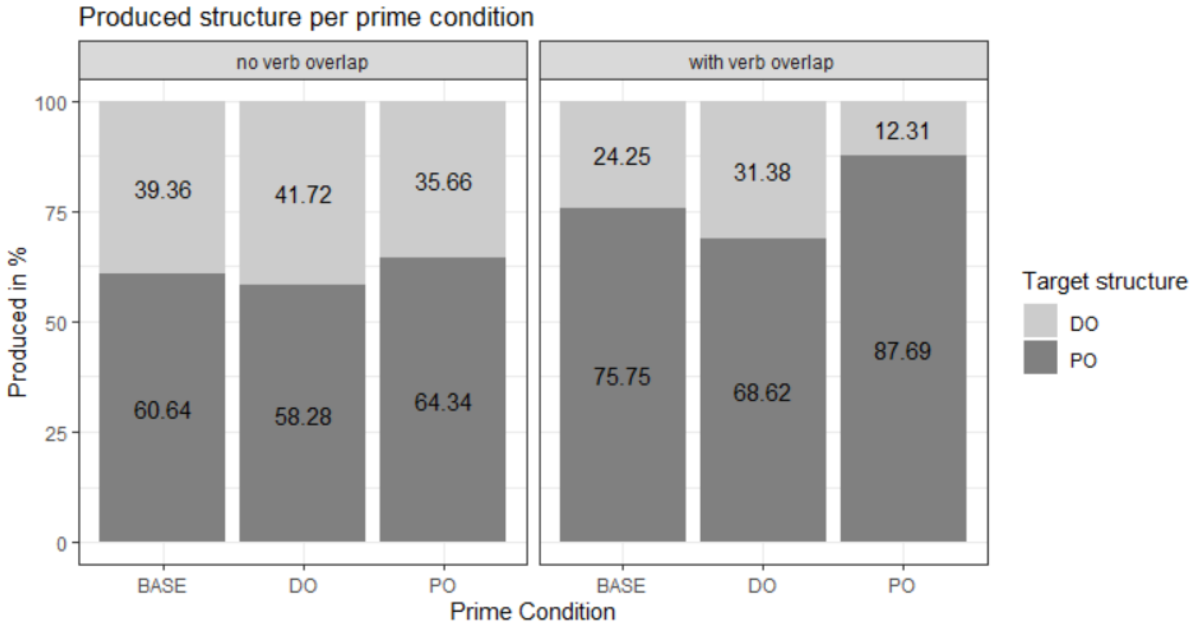
Produced structure per prime condition
no verb overlap
with verb overlap
Produced in %
100
75
50
25
0
39.36
60.64
41.72
58.28
35.66
64.34
24.25
75.75
31.38
68.62
12.31
87.69
BASE
DO
PO
BASE
DO
PO
Prime Condition
Target structure
DO
PO

Figure 7.

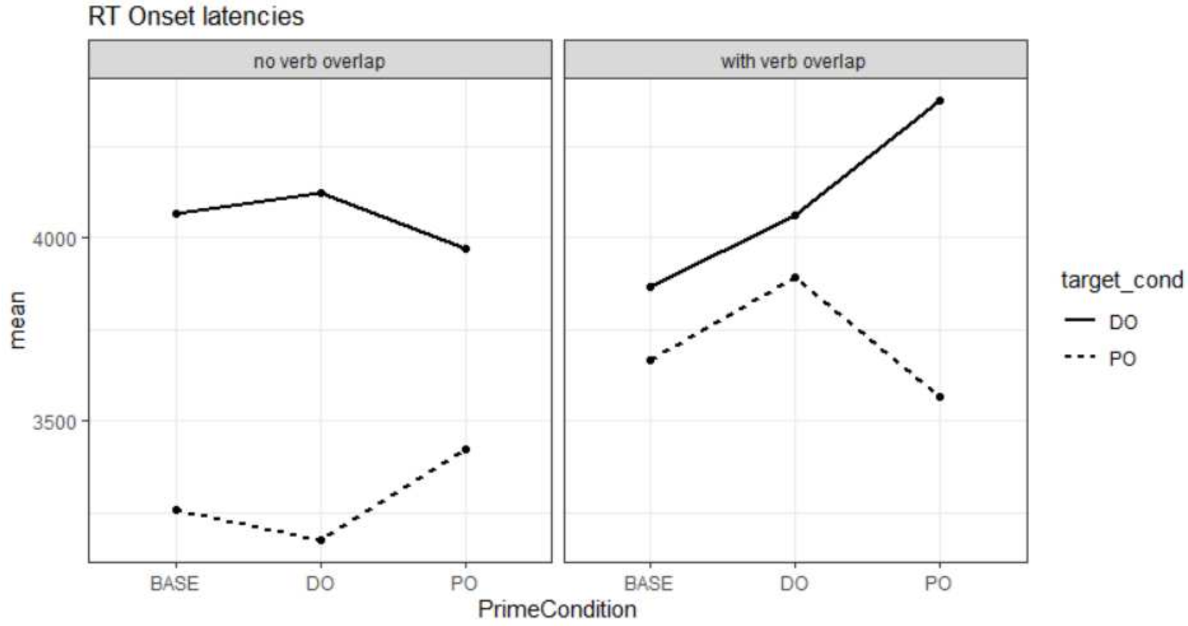
RT Onset latencies
no verb overlap
with verb overlap
mean
4000
3500
BASE
DO
PO
BASE
DO
PO
PrimeCondition
target_cond
DO
PO

Figure captions

- Figure 1. Structural priming according to the two-stage competition model.
- Figure 2. Example of maze task paradigm (with distractor words generated in an automated way).
- Figure 3. Choice for target structure per prime condition
- Figure 4. Reaction times per prime condition (DO targets) in ms.
- Figure 5. Reaction times per prime condition (PO targets) in ms
- Figure 6. Produced structure per prime condition
- Figure 7. Onset latencies per prime and target condition, with/without verb overlap