Primed from the Start:

Syntactic Priming during the First Days of Language Learning

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Running head: Primed from the start

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Abstract

When learning new linguistic information, we need to integrate it within our existing language system. Using a novel experimental task that incorporates a syntactic priming paradigm into an artificial-language learning task, we investigate how new grammatical regularities and words are learned. This innovation allows us to control the language input the learner receives, while the syntactic priming paradigm provides insight into the nature of the underlying syntactic processing machinery. The results of the present study point to facilitatory syntactic processing effects within the first days of learning: syntactic and lexical priming effects reveal participants' sensitivity to both novel word-orders and words. This shows that novel syntactic structures and their meaning (a form-function mapping) can be acquired rapidly through incidental learning. More generally, our study indicates similar mechanisms for learning and processing in both artificial and natural languages, with implications for the relationship between first and second language learning.

Introduction

Unless you sit in a class room being taught a second language, a new language does not come pre-packaged in helpful bits and pieces. Rather, being immersed in a new language environment means handling various aspects of the new language, including new words and new grammatical regularities, all at the same time. Not only do language learners have to learn the meaning of the individual words, they also have to figure out how the structure of sentences maps onto meaning, i.e., "who did what to whom". Thus, the learner has to acquire the mapping between form and function and build corresponding memory representations. The question is, however, whether the mechanisms by which this mapping between form and function is learned differ between first- and second-language learning and thus whether the processing of a second language is fundamentally different if learned after puberty (e.g., different mechanisms: Chomsky, 1965; Clahsen & Felser 2006; same mechanisms: Arnon & Christiansen, 2017; Christiansen & Chater, 2016) . The notion that there is substantial overlap between first- and second-language processing as well as between

first- and second-language learning mechanisms is supported by findings indicating that the same brain regions are recruited for first and second language processing (Indefrey, 2006; Weber & Indefrey, 2009) and that native-like brain signatures of syntactic processing, even in miniature languages, emerge very quickly (Christiansen, Conway, & Onnis, 2012; Morgan-Short, Steinhauer, Sanz, & Ullman, 2011). Thus, it appears that a second language is processed by the same broad neural networks also employed for the first language.

In the current study, we seek to further elucidate the mechanisms of second-language learning in the context of syntactic processing. Specifically, we investigate syntactic priming effects when learning a new, second language to determine whether such priming follows the same patterns as observed during native language learning and processing. As discussed below, we further aim to theoretically link syntactic priming effects to implicit learning as a possible mechanism for learning first and second languages. To this end, we probe syntactic priming effects during the first days of language learning. We hypothesize that syntactic priming is an implicit language learning mechanism (Chang, Dell, Bock, & Griffin, 2000; Chang, Dell, & Bock, 2006), where the repetition of syntactic structure helps the form-function mapping, potentially through error-based learning. Moreover, we explore how different factors such as structure frequency and lexical information influence syntactic priming as the language is being learned. These factors are known to affect as well as interact in native language processing, and we therefore manipulate both in our study in order to better understand their potential role in syntactic learning. As such, we create an environment where multiple aspects of a language are learned at the same time, and in which multiple variables are manipulated at the same time. In this way we strive to get closer to the learning situation a learner would face in real-life, while keeping full experimental control.

As a tool we will use miniature artificial languages (Newman-Norlund, Frey, Petitto, & Grafton, 2006; Opitz & Friederici, 2004; Perek & Goldberg, 2015; Wonnacott, Newport, & Tanenhaus, 2008) as they are an ideal test bed to investigate language learning. The input that the learner receives can be fully controlled, such as the distribution of words and structures in the

language, while retaining the same building blocks as a natural language. Here, we combine an artificial language learning paradigm with a syntactic priming paradigm to study syntactic processing online during language learning. Given the hypothesized role of syntactic priming as a language learning mechanism, we predicted that native-like syntactic priming effects would occur after minimal exposure to novel syntactic structures.

Syntactic priming

Syntactic priming provides evidence that participants are sensitive to specific syntactic constructions and can therefore be used as a tool to investigate syntactic processing. Syntactic priming reflects the facilitation of syntactic processing upon the repetition of syntactic structures (see Ferreira & Bock, 2006 & Pickering & Ferreira, 2008 , for reviews). As such, it is one of many kinds of priming that are found in language processing, and cognition more generally. Typically, repeated exposure to certain stimuli or stimulus feature will lead to behavioural priming effects in the form of improved performance and facilitated processing of the primed information as well as their neural counterpart, repetition suppression effects (Grill-Spector, Henson, & Martin, 2006; Gupta & Cohen, 2002; Henson & Rugg, 2003; Tulving & Schacter, 1990; Wiggs & Martin, 1998). In addition to syntactic priming, priming effects in language processing have also been observed for the repetition of specific word forms and semantic information (Dehaene et al., 2001; Neely, 1991; Rugg, 1985). Syntactic priming effects are found in production on response choices (Bock, 1986) as well as response onset times (Segaert, Menenti, Weber, & Hagoort, 2011; Smith & Wheeldon, 2001). They are also found, albeit somewhat less consistently, in language comprehension (Tooley & Traxler, 2010): on both pictures choices (Branigan, Pickering, & McLean, 2005) as well as on reading times (Weber & Indefrey, 2009). Moreover, syntactic priming effects have been found to known structures in first and second language processing in adults (Hartsuiker, Pickering, & Veltkamp, 2004; Weber & Indefrey, 2009) as well as in children in both language comprehension (Thothathiri & Snedeker, 2008) and production (Branigan & Messenger, 2016; Messenger,

Branigan, McLean, & Sorace, 2012; Rowland, Chang, Ambridge, Pine, & Lieven, 2012). Moreover, novel constructions like "this table needs cleaned" (Kaschak & Glenberg, 2004) are primable as well.

Two previous artificial language learning studies have looked at syntactic priming. Fehér, Wonnacott and Smith (2016) showed abstract structural priming in production within a communicative context after learning an artificial language with novel word orders. Whereas they used a combination of an artificial language and a syntactic priming paradigm as a tool to investigate language change, we employ this combination to investigate language learning mechanisms. We previously reported an fMRI study using a very similar paradigm to the one used here (Weber, Christiansen, Petersson, Indefrey, & Hagoort, 2016) and showed that novel word orders can be primed one day after the first exposure to a miniature language, using both picture choice and neural repetition suppression/enhancement measures. This suggests that novel syntactic representations can be built up very quickly and investigated with syntactic priming during learning. Crucially, though, these two artificial language studies did not investigate the effects during the first moments of exposure to novel grammatical regularities. Moreover, their behavioral measures were restricted to picture and language production choices. In the current study, we investigate these effects in terms of comprehension using both picture choices and reading aloud times. While the picture choices indicates whether syntactic priming facilitates the interpretation of 'who did what to whom', the reading aloud times provides a more direct measure of whether the online processing system is sensitive to the processing of grammatical structures in context.

Syntactic priming as implicit learning

During learning, syntactic priming can be interpreted as an indication of when the processing system has accommodated novel structures because the priming effect shows that the novel grammatical regularity must have a mental representation. Building on implicit learning theory, some theories of syntactic priming, have proposed that syntactic priming might even be a

mechanism for language learning (Chang et al., 2000). The repetition of syntactic structures might help in the mapping of meaning onto form (Ferreira & Bock, 2006) by reducing the error signal that is generated when the input does not match the expected syntactic structure. Thus, syntactic priming effects might be particularly strong during learning. From this follows an additional prediction, the inverse preference effect: priming effects should be stronger for infrequent structures because these benefit most from repetition (Ferreira & Bock, 2006) as an unexpected structure leads to a larger error signal (Chang, Janciauskas, & Fitz, 2012). In both language comprehension (Fine, Jaeger, Farmer, & Qian, 2013) and production (Jaeger & Snider, 2013; Segaert et al., 2011) studies have shown that syntactic priming is sensitive to expectation modulations, such as the frequency of occurrence of a particular structure. This is in line with error-based implicit learning accounts and the inverse preference account. Unexpected information leads to a larger prediction error and hence a larger learning signal.

As mentioned before syntactic priming effects are also found in children (Branigan & Messenger, 2016; Messenger et al., 2012; Rowland et al., 2012; Thothathiri & Snedeker, 2008), from as early as 3 years of age (Rowland, Chang, Ambridge, Pine, & Lieven, 2012). Thus, syntactic priming might be a learning mechanism for syntactic structures that is present throughout life, driving the acquisition of grammatical structures in first languages as well as second languages and facilitating the processing of known syntactic structures. However, both in adults and children syntactic priming effects have mainly been studied using syntactic structures with which the participants had at least some experience. To link these priming effects to learning, a key aim of this paper is therefore to show that these effects are present from the very beginning of learning a new syntactic structure.

Lexical influences on syntactic learning?

In its original form, the implicit learning theory is a purely structural account, independent of lexical representations. Other theories, like the residual activation account (Pickering & Branigan,

1998), link syntactic priming to the activation of syntactic frames which are tied to lexical representations. This implies that syntactic processing is lexically guided (Jackendoff, 2002; MacDonald, Pearlmutter, & Seidenberg, 1994) and that verb repetition therefore will boost syntactic priming effects (Pickering & Branigan, 1998). However, syntactic priming is also found with novel or morphologically anomalous verbs (Ivanova, Pickering, Branigan, McLean, & Costa, 2012), indicating that there are at least some lexically-independent components to syntactic priming.

Even if there is lexically-independent syntactic processing in a learned language, syntactic priming linked to verb repetition might be helpful during language acquisition because of the additional boosting of the mapping process between form and meaning. This could be because of a strong lexical contribution or even lexical-specificity at the beginning of learning (Savage, Lieven, Theakston, & Tomasello, 2003; Tomasello, 2000). However, in first language acquisition, many syntactic priming studies have found verb-independent priming effects (Branigan & McLean, 2016; Huttenlocher, Vasilyeva, & Shimpi, 2004; Messenger et al., 2012; Peter, Chang, Pine, Blything, & Rowland, 2015; Rowland et al., 2012) indicating some lexical independence of syntactic learning in addition to a lexical boost of the priming effect (Branigan & McLean, 2016; Rowland et al., 2012).

The current study

In this study, participants were exposed to a novel language, which they learned in four sessions over the course of nine days. They read sentences with novel lexical items occurring in novel transitive word-orders. Participants could infer the meaning of these sentences from accompanying pictures. This allowed them to map the subject, object and verb of the transitive sentences onto the agent, patient and action that they saw in the pictures. To make lexical learning as easy as possible the novel language had the same mapping of persons to nouns and actions to verbs as their native language. The experimental manipulation consisted of both sentence structure and lexical repetition. To test the inverse preference account, we added a frequency manipulation on the first day of

exposure to the sentences. Priming effects were investigated on a picture-choice task, a measure of how well participants understood the meaning of the sentences. In addition, the effects of priming on reading aloud times were measured. This processing-based measure allows for conclusions about the nature of online processing during learning. We chose reading aloud times instead of the more standard reading times via button presses in order to keep the exposure to the sentences the same for all participants during learning.

Predictions

We asked whether we would find syntactic priming effects on the responses of the picture choice-task, in the form of increased performance after priming, as well as on the processing-based measure of reading aloud times, in the form of faster reading aloud times after priming. This would be in line with priming effects in first language acquisition, as well as in first and second language processing. If novel syntactic structures are quickly integrated into the language processing system, we expect the priming effects to known and novel structures to resemble each other early on. We were particularly interested in whether syntactic priming effects occur on the first day and during the first hour of exposure to novel syntactic regularities. This would point to a link between syntactic priming and syntactic learning, facilitating the mapping of syntactic form onto function (meaning). The reading aloud time effects might get stronger across days, as processing gets further facilitated over the course of learning, while the effects on the picture choices might reach ceiling level over time once participants have become proficient comprehenders of the new language. In addition, we also expect lexical repetition of verbs to result in priming effects, which would reflect the learning and integration of the novel lexical information.

Moreover, we will investigate whether syntactic processing during the early stages of learning is lexically-bound, lexically-mediated or lexically independent. More specifically, if syntactic learning is helped by lexical-syntactic information, then we should find a lexical mediation to syntactic priming effects from the first day of exposure. If however, more abstract

syntactic structures can be learned independently, syntactic priming effects might only become lexically-mediated over time, if at all. We therefore track syntactic priming effects during learning over multiple days.

And furthermore, in line with the inverse preference account of syntactic priming and its potential link to error-based learning, we expect stronger priming effects for the infrequent syntactic structure. However, as some minimal exposure to a structure might be necessary to produce a priming response, it might also be the case that the more frequent structure will initially show the stronger effect.

Methods

Participants

In this study, we tested 27 Dutch native speakers (21 female, 6 male), one participant was subsequently excluded from the analysis as the sound files were not properly recorded. Three additional participants started the experiment but did not complete all days. All participants had normal or corrected to normal vision. The participants received course credits or money for their participation. All participants gave informed consent prior to participating.

Materials

The artificial language consisted of 36 transitive verbs, 10 intransitive verbs, and 4 nouns (example words and sentences can be seen in Figure 1 and Appendix A, Table 1 and Table 2). There were 4 different types of sentence structures in this language. Two were novel transitive word-orders that are not permissible for Dutch transitive sentences. These word-orders were verb-object-subject (VOS) and object-subject-verb (OSV). A third transitive word-order was subject-verb-object (SVO), the ‘active’ word-order in Dutch and thus known to the participants. The fourth sentence structure was an intransitive subject-verb (SV) word-order, also present in Dutch, and used in filler sentences. All subjects and objects were animate (man, woman, girl, boy).

Lexical items were novel with an easy to produce syllabic structure (e.g. *basi, kisu, epaki, hakaro*). A list of lexical items was rated by six Dutch native speakers and those that resembled Dutch or otherwise meaningful words were removed. The assignment of meaning to the different words was counterbalanced across subjects (there were 8 different word-referent assignment lists) as was the selection of which of the new word orders was the frequent structure on Day 2. Day 1 was an introductory day where participants learned the four nouns (see *Procedure*), On Day 2, the experimental lists contained 20 trials (prime-target pairs) for the frequent word-order condition and 10 each for the infrequent and known word-orders (per verb and syntactic priming condition). The lists for Day 3 and Day 9 contained 20 trials per condition.

The sentences described events depicted in black and white photographs. There were 8 possible depictions of each event. These were created using two sets of actor pairs (girl/boy and woman/man), where the agent was either the male or the female actor and where the agent was either located to the left or to the right in the picture.

Procedure

Participants took part in the experiment on four different days, Day 1, 2, 3 and 9. They were told that they were going to learn a new language, "Alienese".

The experiment was run using Presentation software (Neurobehavioral Systems, www.neuro-bs.com). Participants sat in front of a desktop computer. Words and sentences were presented in white "Arial" font of size 22 on a black background.

On Day 1, participants learned the four nouns, the words for man, woman, boy and girl by means of a picture-word matching paradigm. First, each word was given with a matching picture 6 times, all nouns intermixed. To verify the learning, the pictures were then given with the 4 possible nouns. Participants had to choose the matching noun by a button press. Participants had learned all four nouns by the end of this noun learning session (after six more repetitions of each noun). For one subject the whole procedure was repeated again, as she was not a 100% correct after the first

round of exposure. The verbs were not taught explicitly, they were learned during exposure to the sentences on the subsequent days.

Training session

On Day 2, participants took part in a sentence training session. 80% of the sentences were experimental items and 20% were filler sentences (intransitives). In total, including filler sentences, word-order 1 (counterbalanced across participants, in half of the participants word-order 1 was VOS in the other half OSV) occurred 40% of the time and the other three word orders (word-order 2, known word-order, SVO, and intransitive word-order, SV) each 20% of the time. By having one of the word orders appear twice as often as each of the other syntactic structures (including fillers), we can study the potential effects of structural frequency on syntactic priming during the initial phase of learning. Participants were asked to read the sentences aloud and we recorded their responses. Pictures and sentences were displayed simultaneously (the picture was presented in the middle of the screen and the sentence was presented in the middle of the bottom half of the screen overlapping the picture). A picture-sentence trial would start with a fixation cross being displayed for 2 seconds followed by the sentence and picture which were displayed simultaneously for 4 seconds. To mirror the manipulations of the following days, we included lexical and syntactic priming manipulations. Both verbs and word-orders were repeated in half of the cases, orthogonally to each other. The nouns were never repeated in subsequent sentences. Sentences containing the woman and the man alternated with those containing the boy and the girl, each sentence structure would thus occur with both noun combinations. Verbs were randomly assigned to a trial and each transitive verb would occur in all transitive structures.

Experimental sessions

On Day 3 and Day 9, participants took part in the experimental sessions. Here, all word-orders occurred equally often. On these days, the picture was displayed after the sentence (see Figure 1). A fixation cross would be displayed for an average of 1.7 seconds, followed by the sentence for 2 seconds, then by a blank screen for 1 second, and subsequently a picture describing

the sentence for 3 seconds (4 seconds if it was a target with 2 pictures). The limited temporal jitter was introduced between the fixation cross and the blank screen because we wanted to test the paradigm for an fMRI version of this study.

In addition to reading aloud, the subjects also had to perform a comprehension task. After a target sentence, the participants were presented with two pictures. Both pictures depicted the same action with the same actors, but the roles of the actors (agent and patient) were reversed. Participants were asked to decide which of the pictures matched the preceding sentence by pressing one of two buttons with their left and right index fingers. In all three sessions, on Day 2, 3 and 9, the priming manipulations were the same. Our priming manipulations involved immediate repetition (or non-repetition), between prime and target, of syntactic structure, the verb, or both. At the end of the sessions on Day 2, 3 and 9, participants received a pen and paper questionnaire with all 46 Alienese verbs. They were asked to translate these verbs into Dutch.

The onset times were measured online using a voice key and saved in a logfile. Speech offset values were determined by applying a semi-automatic method in Praat (ww.praat.org) to the recorded sound files. A script determined speech offset times based on loudness. Subject-specific parameters for this calculation were determined using random spot checks. Following this, onset and offset times that were more than 3 standard deviations different from the mean were manually checked for errors. This procedure was done twice in a row. Where identified, sound files that contained coughs, hesitations and repairs were removed from the analysis. These trials were also removed from the analysis of picture choices.

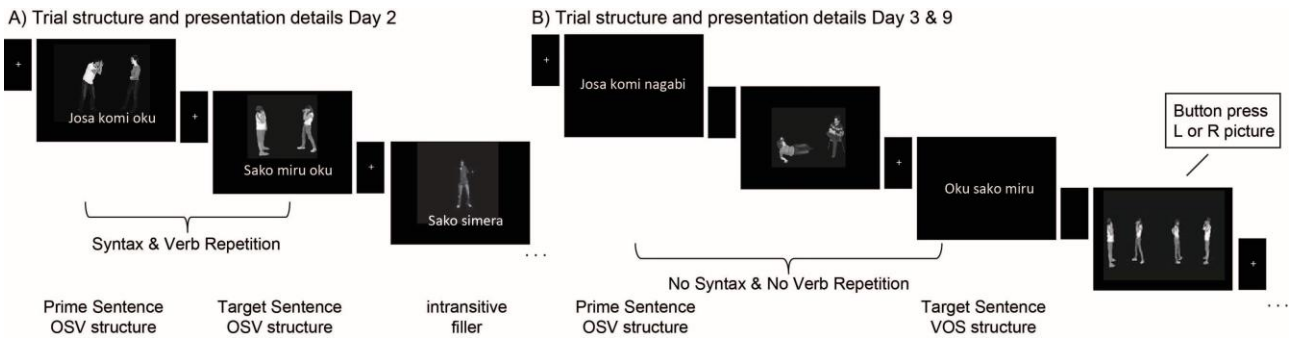

Figure 1. A) Trial structure on Day 2. A sentence-picture pairing started with a fixation cross followed by a screen displaying both the picture and the sentence simultaneously. An example of a trial is shown where both syntax and verb are repeated between prime and target (OSV sentence structure; the verb is 'oku': to photograph). B) Trial structure on Day 3 and Day 9. A sentence-picture pairing started with a fixation cross followed by the sentence. After a blank image a picture was presented. On target trials two pictures were presented simultaneously and participants had to choose the one corresponding to the preceding sentence. An example of a trial is shown where neither the syntax (prime OSV, target VOS structure) nor the verb is repeated (prime 'nagabi': to draw, target 'oku': to photograph).

Results

Verb translation

Participants improved in translating the verbs from 'Alienese' into Dutch from Day 2 to Day 9 (Means for Day 2: 27.98%, Day 3: 48.96%, Day 9: 64.76%).

Priming analyses

We analyzed the picture choices using mixed-effects logit models (Barr, Levy, Scheepers, & Tily, 2013; Jaeger, 2008; Pinheiro & Bates, 2000) and the overall reading aloud times on Day 2, 3 and 9 (from the start of sentence presentation to reading offset) using a mixed effects model with random effects for subjects and items in R (R Development Core Team, 2012). Following (Barr et al., 2013), we used a model with the maximal effect structure that was still converging. When a model did not converge, we removed random slopes for factors with the lowest variance first. For contrast specifications, Helmert coding was used (for 2 levels equivalent to deviation coding), where each level of a categorical variable is compared to the mean of the subsequent levels. This coding was adopted to ensure that for the factor 'Type of Sentence' we could address two key questions related to our predictions: 1) whether the effects for known structures are different from novel ones, and 2)

whether there is a difference between frequent and infrequent novel structures. In the text, we only report effects for the contrasts of interest. A full list of all fixed effects for all analyses is reported in the appendix (Appendix A: Table 3, 4 and 5).

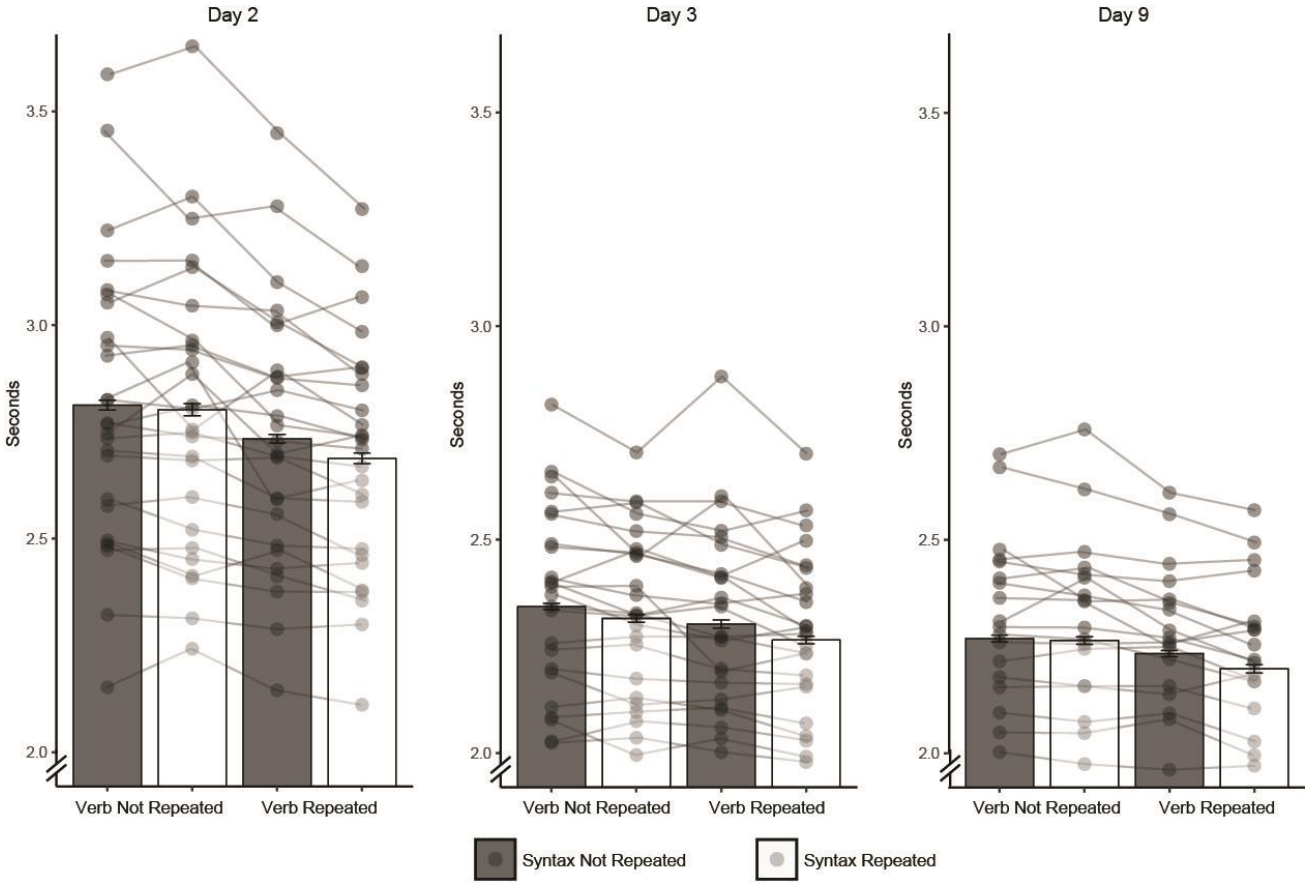

Figure 2. Overall reading aloud times (from text display onset to reading offset) on Day 2, 3 and 9 for the verb and syntax repetition conditions. The error bars show the standard error of the mean. Dots and lines represent individual subjects' performance.

Overall reading aloud times over all days

The model of the overall reading aloud times on Day 2, 3 and 9 included fixed effects for Day (Day 2, Day 3, Day 9), Type of Sentence (Frequent, Infrequent, Known), Verb (Verb Repeated, Not Repeated) and Syntax (Syntax Repeated, Not Repeated) and allowed interactions between all of these. The random effects structure included a random intercept for subjects and items and random slopes for Day and Type of Sentence for subjects as well as for items. A summary of the fixed effects can be found in Appendix A (Table 3 and Figure 1).

Main effect of Verb repetition

Participants were significantly faster if the verb (β =-.06, SE= .01, t=-11.07, p<.001) was repeated.

Main effect of Syntax repetition (and Day)

Participants were significantly faster if the syntax (β =-.03, SE=.01, t=-4.71, p<.001) was repeated. This effect did not differ across days, both |t|<1.

Interaction Verb and Syntax repetition (and Day and Type of Sentence)

There was a significant interaction between Verb and Syntax (β =-.02, SE=.01, t=-2, p=.045): if the verb was repeated there was a large syntactic repetition effect, β =-.036, SE=.007, t=-4.9, p<.001, while there was a marginally significant syntactic repetition effect if the verb was not repeated, β =-.015, SE=.008, t=-1.9, p=.06. The three-way interactions between Day, Verb and Syntax were not significant, t=1.11 and |t|<1. The Verb by Syntax interaction did not differ between known and novel word orders, |t|<1.

Interaction Type of Sentence and Syntax repetition (and Day)

The interactions between Type of Sentence and Syntax were not significant, both |t|<1. There was also no further interaction with the factor Day, both |t|<1.

Overall reading aloud times Day 2

As we were specifically interested to see whether syntactic and verb priming effects would already be strongly present on the first day of learning, thus indicating their importance for learning form-function mappings, we ran a separate model for this day only. The model of the overall reading aloud times on Day 2 included fixed effects for Type of Sentence (Frequent, Infrequent, Known), Verb (Verb Repeated, Not Repeated) and Syntax (Syntax Repeated, Not Repeated) and allowed interactions between all of these. The random effects structure included a random intercept for subjects and items and no random slopes (as the model including the random slope with the highest variance did not converge). A summary of all the fixed effects can be found in Appendix A (Table 4 and Figure 1).

Main effect of Verb repetition

Participants were significantly faster if the verb (β=-.04, SE=.01, t=-7.14, p<.001) was repeated.

Main effect of syntax repetition

Participants were significantly faster if the syntax (β=-.01, SE=.01, t=-2.62, p=.009) was repeated between prime and target (see Figure 2).

Interaction Verb and Syntax repetition (by Type of Sentence)

While numerically the syntactic repetition effect was larger in case of verb repetition, the interaction between Verb and Syntax repetition was not significant, t=-1.46, neither were the interactions between Verb, Syntax and Type of Sentence, |t|<1.

Interaction Type of Sentence and Syntax repetition

The interactions between Type of Sentence and Syntax were not significant, both |t|<1.

Picture Choices Day 3 and 9

The model for the picture choices included fixed effects for Day (Day 3, 9), Type of Sentence (Frequent, Infrequent, Known), Verb (Verb Repeated, Not Repeated) and Syntax (Syntax Repeated, Not Repeated) and allowed interactions between all of these. The random effects structure included a random intercept for subjects and items and random slopes for Type of Sentence and Day for subjects and item. A summary of all fixed effects can be found in Appendix A (Table 5 and Figure 2).

Main effect of Verb repetition

Participants were significantly better in making the correct choice if the verb (β =.24, SE=.06, Z=3.82, p<.001) was repeated.

Main effect of Syntax repetition (and Day)

Participants were also significantly better in making the correct choice if the syntactic structure (β =.38, SE=.07, Z=5.43, p<.001) was repeated. The syntactic repetition effect decreased slightly on Day 9 (β =-.39, SE=.13. Z=-2.95, p<.001).

Interaction Verb and Syntax repetition (and Day/Type of Sentence)

Verb repetition gave a boost to the syntactic repetition effect, but this effect was only marginally significant, β =.23, SE=.13, Z=1.83, p=.07 (see Figure 3). If the verb was repeated there was a large syntactic repetition effect, β =.49, SE=.09, t=5.1, p<.001, nonetheless there was a still a significant syntactic repetition effect if the verb was not repeated, β =.26, SE=.08, Z=3.1, p=.002. The interaction effect between Verb and Syntax was larger on Day 3 than on Day 9, β =-.52, SE=.25, Z=-2.06, p=.04, as well as larger for the known compared to the novel structures, β =.98, SE=.27, Z=3.6, p<.001. For the known structures the Verb by Syntax interaction was significant (β=0.88, SE=0.22, Z=4.03, p<.001), while for the novel structures the interaction between Verb and Syntax was not significant (|Z|<1).

Interaction Type of Sentence and Syntax repetition (and Day)

The syntactic repetition effect was slightly larger if the target sentences had a known sentence structure (β =.36, SE=.14, Z=2.56, p=.01). Moreover, the syntactic repetition effect to the frequent structure was larger than to the infrequent structure (β=.32, SE=.15, Z=2.07, p=.04). Given, the interactions, we looked at the syntactic repetition effect for each structure separately. It was significant for the known structure (β=0.63, SE=0.11, Z=5.76 p<.001), and the frequent structure (β=0.41, SE=0.11, Z=3.83, p<.001), but not for the infrequent structure, Z<1.

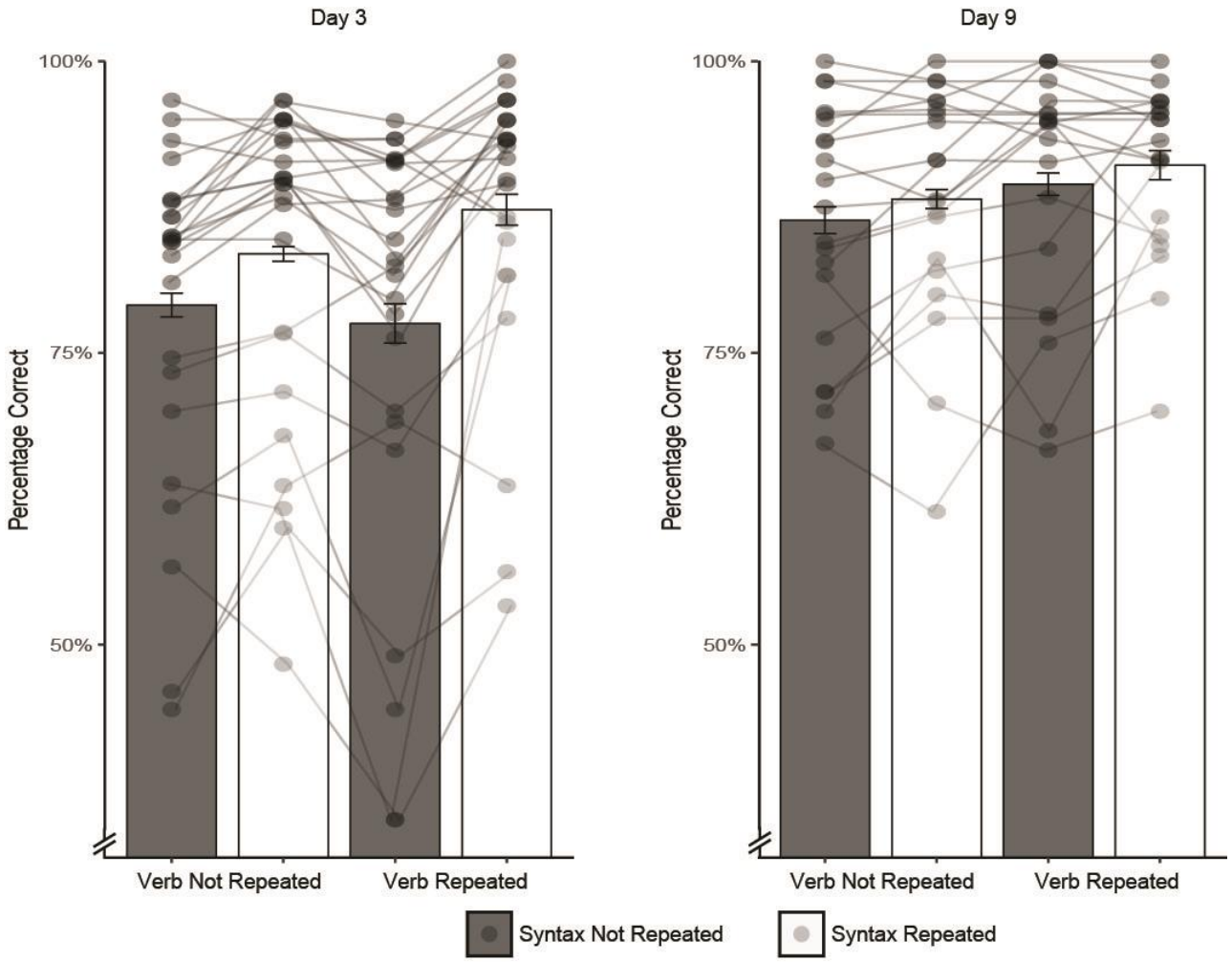

Figure 3. Picture choices for Day 3 and Day 9 for the verb and syntax repetition conditions. The error bars show the standard error of the mean. Dots and lines represent individual subjects' performance.

Discussion

In this study, we have shown that language learners can acquire novel word-orders and new lexical items very quickly. Although the meaning was only provided in the form of pictures, participants were able to extract this information from the novel language. Both the meaning of the verbs and the syntactic structures were learned to a high level of proficiency (65% correct verb translations and 89% correct on the picture choice task on the last day).

Effects of verb and syntactic repetition

Both verb and syntactic priming effects were found on the overall reading aloud times of the sentences. This measure of overall processing time might reflect the online efficiency of the language processing system, which is facilitated by repetition (Christiansen & Chater, 2016). Our results show that language learners become sensitive to the underlying syntactic structures very quickly, within the first hour of exposure—the syntactic priming effect was significant from the first day of exposure to the sentences—even if those structures are not given to the learner explicitly.

Moreover, similarly to our previous fMRI study using this paradigm in the scanner and looking at hemodynamic repetition effects (Weber et al., 2016), verb and syntactic priming effects were found on the picture choice measure, indicating that the repetition of both lexical as well as syntactic information helps in understanding novel linguistic information. The picture-choice measure can be construed as reflecting the outcome of the syntactic processing, as the picture choice is made after an interpretation is established. Lexical and syntactic repetitions seem to facilitate the mapping of form onto meaning, thus leading to an improved interpretation.

Mechanisms of priming and learning

Mechanistically, behavioural priming effects might be the results of neural repetition effects as found in our previous fMRI study (Weber et al., 2016). The repetition of novel information might strengthen the creation of a novel memory representation (Henson, Shallice, & Dolan, 2000) of the distributional pattern of a syntactic structure (i.e., the order of the grammatical roles) and/or the mapping onto thematic roles and their links to meaning. Alternatively, predictive coding theories (Friston, 2005) or error-based learning theories (Chang et al., 2006) can account for priming effects. In such theories, prediction errors generated between an expected event, such as a syntactic structure, and the actual syntactic structure encountered, are useful learning signals. Repetition of information then leads to reductions in prediction error, which manifests itself in priming or neural

repetition effects (Auksztulewicz & Friston, 2016). That syntactic priming effects are found from the start of exposure thus supports the idea that syntactic priming plays a role in language learning (Bock & Griffin, 2000; Chang et al., 2000; Ferreira & Bock, 2006), as it shows that it supports a form-function mapping and the building of a novel memory representation from the earliest moments.

However, the implicit learning account of syntactic priming also predicts that the infrequent structure should have shown a stronger syntactic priming effect (Chang et al., 2012; Ferreira & Bock, 2006). We did not observe such an effect here; rather syntactic priming effects on reading aloud times were similar for all structures (however, see Weber and colleagues 2016 for differences in neural, fMRI, priming effects using a similar paradigm). Moreover, on the picture choices a syntactic repetition effect was present for known and frequent structures but not the infrequent ones, indicating that at least a certain level of exposure has to be reached before structural priming can lead to a benefit in understanding the meaning of the sentences. The syntactic priming effect on the picture choices appears to level off on Day 9. This is most likely due to a ceiling effect as participants make very few mistakes (11% on Day 9), leaving little room for improvement due to priming.

Lexical influences on syntactic learning?

In native language processing, syntactic priming effects are sometimes boosted by verb repetition (Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008; Pickering & Branigan, 1998), hinting at a lexical mediation of some syntactic processing effects. During first language acquisition in young children (3-4 year olds), there is some evidence of lexically bound syntactic priming effects (Savage et al., 2003) whereas other studies find verb-independent syntactic priming effects (Branigan & McLean, 2016; Huttenlocher et al., 2004; Messenger et al., 2012; Rowland et al., 2012), showing that syntactic structures can be learned independently of verb-specific information. Nevertheless, a lexical boost to the syntactic priming effect is often found also in children, both in

comprehension and production (Branigan & McLean, 2016; Thothathiri & Snedeker, 2008) but its onset might be slightly later (Rowland et al., 2012). In the present study, we found the verb boost on syntactic priming for a known syntactic structure within a novel language on the picture choice measure. However, no verb boost effect was found for the novel syntactic structures using this measure. On the other hand, the reading aloud times revealed a verb boost to the syntactic priming effect, which did not differ between novel and known syntactic structures. When looking at the first day of learning on its own, there was not a verb boost effect but a verb-independent syntactic priming effect. Thus, verb-independent syntactic priming effects for novel structures were found on all measures starting on the first day of exposure to the sentences. This suggests that in the first days of experience with a new structure, the structure may not be lexically-bound. Rather, it seems that some amount of generalization to other verbs occurs. This in turn suggests that sensitivity to more general distributional regularities relating to the different word-orders is established early in learning. This is thus in line with theories that link syntactic priming effects to implicit learning mechanisms (Chang et al., 2006) but seemingly inconsistent with a strong account of lexically-bound syntactic learning (Tomasello, 2000).

These results show that the syntactic priming effects for novel structures in a miniature language very early on display similar patterns to those obtained during first language learning and processing. Abstract syntactic priming effects were found from the start, while a verb boost effect was present after some exposure to the artificial language. More generally, the syntactic priming effects for novel structures on both the picture choice and the reading aloud time measures, show that these effects can be employed as a tool to investigate syntactic processing during language learning using an artificial miniature language.

Limitations and future directions

This study is a first foray into investigating syntactic priming effects as a learning mechanism during the first hours of language learning. Consequently, this initial design has certain limitations that should be considered in future studies on this topic.

As a processing-based measure, we used a reading aloud measure to be able to control the timing of the input during learning. However, in the future, finer grained measures, such as word-by-word self-paced reading times could be used or a combination of comprehension and production measures. Moreover, it may also be of value to link the strength of syntactic priming effects during learning to the learning outcomes by having more nuanced behavioural measures of learning (in the current version many participants perform at ceiling on the picture choice task on the last day). Furthermore, the reading-based nature of our design (with the reading aloud task) does not resemble the typical learning situation in first-language acquisition as well as in immersion-based second-language learning scenarios. Thus, it may be useful to adapt our experimental paradigm to a more speech-based format in future studies of the role of syntactic priming in language production as well as language learning more generally.

Conclusions

In sum, syntactic priming effects appear early during the learning of novel syntactic structures and reveal an early sensitivity to these structures. The speed at which novel word-orders can be extracted from the input suggests a general sensitivity to sequence structure that is not fixed for life by the long-term experience with the dominant native language. Moreover, it suggests that similar mechanisms are in place for first and second language acquisition and that artificial language learning paradigms can be used to study both kinds of language learning.

References

Arnon, I., & Christiansen, M. H. (2017). The role of multiword building blocks in explaining L1-L2 differences. *Topics in Cognitive Science, 9*, 621-636. doi: https://doi.org/10.1111/tops.12271

Auksztulewicz, R., & Friston, K. (2016). Repetition suppression and its contextual determinants in predictive coding. *Cortex, 80*, 125-140. doi: http://dx.doi.org/10.1016/j.cortex.2015.11.024

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255-278. doi: http://dx.doi.org/10.1016/j.jml.2012.11.001

Bock, J. K. (1986). Syntactic persistence in language production. *Cognitive Psychology, 18*(3), 355-387. doi: https://doi.org/10.1016/0010-0285(86)90004-6

Bock, J. K., & Griffin, Z. M. (2000). The persistence of structural priming: transient activation or implicit learning? *Journal of Experimental Psychology: General, 129*(2), 177-192. doi: https://doi.org/10.1037//0096-3445.129.2.177

Branigan, H. P., & McLean, J. F. (2016). What children learn from adults' utterances: An ephemeral lexical boost and persistent syntactic priming in adult–child dialogue. *Journal of Memory and Language, 91*, 141-157. doi: http://dx.doi.org/10.1016/j.jml.2016.02.002

Branigan, H. P., & Messenger, K. (2016). Consistent and cumulative effects of syntactic experience in children's sentence production: Evidence for error-based implicit learning. *Cognition, 157*, 250-256. doi: http://dx.doi.org/10.1016/j.cognition.2016.09.004

Branigan, H. P., Pickering, M. J., & McLean, J. F. (2005). Priming prepositional-phrase attachment during comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(3), 468. doi: http://dx.doi.org/10.1037/0278-7393.31.3.468

Chang, F., Dell, G. S., Bock, J. K., & Griffin, Z. M. (2000). Structural priming as implicit learning: a comparison of models of sentence production. *Journal of Psycholinguistic Research, 29*(2), 217-229. doi: https://doi.org/10.1023/A:1005101313330

Chang, F., Dell, G. S., & Bock, K. (2006). Becoming syntactic. *Psychological Review, 113*(2), 234-272. doi: http://doi.org/10.1037/0033-295x.113.2.234

Chang, F., Janciauskas, M., & Fitz, H. (2012). Language adaptation and learning: Getting explicit about implicit learning. *Language and Linguistic Compass, 6*(5), 259-278. doi: 10.1002/lnc3.337

Chomsky, N. (1965). *Aspects of the Theory of Syntax*. Cambridge, Mass: MIT Press.

Christiansen, M. H., & Chater, N. (2016). *Creating language: Integrating evolution, acquisition, and processing*: MIT Press.

Christiansen, M. H., Conway, C. M., & Onnis, L. (2012). Similar neural correlates for language and sequential learning: Evidence from event-related brain potentials. *Language and Cognitive Processes, 27*(2), 231-256. doi: http://doi.org/10.1080/01690965.2011.606666

Clahsen, H., & Felser, C. (2006). How native-like is non-native language processing? *Trends in Cognitive Sciences, 10*(12), 564-570. doi: http://dx.doi.org/10.1016/j.tics.2006.10.002

Dehaene, S., Naccache, L., Cohen, L., Bihan, D. L., Mangin, J. F., Poline, J. B., & Riviere, D. (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Neuroscience, 4*(7), 752-758. doi: https://doi.org/10.1038/89551

Fehér, O., Wonnacott, E., & Smith, K. (2016). Structural priming in artificial languages and the regularisation of unpredictable variation. *Journal of Memory and Language, 91*, 158-180. doi: https://doi.org/10.1016/j.jml.2016.06.002

Ferreira, V., & Bock, K. (2006). The functions of structural priming. *Language and Cognitive Processes, 21*(7-8), 1011-1029. doi: http://doi.org/10.1080/01690960600824609

Fine, A., Jaeger, T. F., Farmer, T. A., & Qian, T. (2013). Rapid Expectation Adaptation during Syntactic Comprehension. *PLoS One, 8*(10), e77661. doi: http://doi.org/10.1371/journal.pone.0077661

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B-Biological Sciences, 360*(1456), 815-836. doi: http://doi.org/10.1098/Rstb.2005.1622

Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences, 10*(1), 14-23. doi: http://doi.org10.1016/j.tics.2005.11.006

Gupta, P., & Cohen, N. J. (2002). Theoretical and computational analysis of skill learning, repetition priming, and procedural memory. *Psychological Review, 109*(2), 401-448. doi: http://doi.org/10.1037/0033-295x.109.2.401

Hartsuiker, R. J., Bernolet, S., Schoonbaert, S., Speybroeck, S., & Vanderelst, D. (2008). Syntactic priming persists while the lexical boost decays: Evidence from written and spoken dialogue. *Journal of Memory and Language, 58*(2), 214-238. doi: http://dx.doi.org/10.1016/j.jml.2007.07.003

Hartsuiker, R. J., Pickering, M. J., & Veltkamp, E. (2004). Is Syntax Separate or Shared Between Languages?: Cross-Linguistic Syntactic Priming in Spanish-English Bilinguals. *Psychological Science, 15*(6), 409-414. doi: http://doi.org/10.1111/j.0956-7976.2004.00693.x

Henson, R. N., & Rugg, M. D. (2003). Neural response suppression, haemodynamic repetition effects, and behavioural priming. *Neuropsychologia, 41*(3), 263-270. doi: https://doi.org/10.1016/S0028-3932(02)00159-8

Henson, R. N., Shallice, T., & Dolan, R. (2000). Neuroimaging evidence for dissociable forms of repetition priming. *Science, 287*(5456), 1269-1272. doi: http://doi.org/10.1126/science.287.5456.1269

Huttenlocher, J., Vasilyeva, M., & Shimpi, P. (2004). Syntactic priming in young children. *Journal of Memory and Language, 50*(2), 182-195. doi: https://doi.org/10.1016/j.jml.2003.09.003

Indefrey, P. (2006). A Meta-analysis of Hemodynamic Studies on First and Second Language Processing: Which Suggested Differences Can We Trust and What Do They Mean? *Language Learning, 56*, 279-304. doi: http://doi.org/10.1111/j.1467-9922.2006.00365.x

Ivanova, I., Pickering, M. J., Branigan, H. P., McLean, J. F., & Costa, A. (2012). The comprehension of anomalous sentences: Evidence from structural priming. *Cognition, 122*(2), 193-209. doi: https://doi.org/10.1016/j.cognition.2011.10.013

Jackendoff, R. (2002). *Foundations of Language: Brain, Meaning, Grammar, Evolution*. New York: Oxford University Press.

Jaeger, T. F. (2008). Categorical Data Analysis: Away from ANOVAs (transformation or not) and towards Logit Mixed Models. *Journal of Memory and Language, 59*(4), 434-446. doi: http://doi.org10.1016/j.jml.2007.11.007

Jaeger, T. F., & Snider, N. E. (2013). Alignment as a consequence of expectation adaptation: syntactic priming is affected by the prime's prediction error given both prior and recent experience. *Cognition, 127*(1), 57-83. doi: https://doi.org/10.1016/j.cognition.2012.10.013

Kaschak, M. P., & Glenberg, A. M. (2004). This construction needs learned. *Journal of Experimental Psychology: General, 133*(3), 450-467. doi: http://doi.org/10.1037/0096-3445.133.3.450

MacDonald, M. C., Pearlmutter, N. J., & Seidenberg, M. S. (1994). The lexical nature of syntactic ambiguity resolution. *Psychological Review, 101*, 676-703. doi: https://doi.org/10.1037//0033-295x.101.4.676

Messenger, K., Branigan, H. P., McLean, J. F., & Sorace, A. (2012). Is young children's passive syntax semantically constrained? Evidence from syntactic priming. *Journal of Memory and Language, 66*(4), 568-587. doi: http://dx.doi.org/10.1016/j.jml.2012.03.008

Morgan-Short, K., Steinhauer, K., Sanz, C., & Ullman, M. T. (2011). Explicit and Implicit Second Language Training Differentially Affect the Achievement of Native-like Brain Activation Patterns. *Journal of Cognitive Neuroscience, 24*(4), 933-947. doi: http://doi.org/10.1162/jocn_a_00119

Neely, J. H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner, Humphreys, G.W. (Ed.), *Basic Processes in Reading and Visual Word Recognition* (pp. 264-333). Hillsdale, NJ: Erlbaum.

Newman-Norlund, R. D., Frey, S. H., Petitto, L.-A., & Grafton, S. T. (2006). Anatomical Substrates of Visual and Auditory Miniature Second-language Learning. *Journal of Cognitive Neuroscience, 18*(12), 1984-1997. doi: http://doi.org/10.1162/jocn.2006.18.12.1984

Opitz, B., & Friederici, A. D. (2004). Brain Correlates of Language Learning: The Neuronal Dissociation of Rule-Based versus Similarity-Based Learning. *The Journal of Neuroscience, 24*(39), 8436-8440. doi: http://doi.org/10.1523/jneurosci.2220-04.2004

Perek, F., & Goldberg, A. E. (2015). Generalizing beyond the input: The functions of the constructions matter. *Journal of Memory and Language, 84*(Supplement C), 108-127. doi: https://doi.org/10.1016/j.jml.2015.04.006

Peter, M., Chang, F., Pine, J. M., Blything, R., & Rowland, C. F. (2015). When and how do children develop knowledge of verb argument structure? Evidence from verb bias effects in a structural priming task. *Journal of Memory and Language, 81*(Supplement C), 1-15. doi: https://doi.org/10.1016/j.jml.2014.12.002

Pickering, M. J., & Branigan, H. P. (1998). The Representation of Verbs: Evidence from Syntactic Priming in Language Production. *Journal of Memory and Language, 39*(4), 633-651. doi: http://dx.doi.org/10.1006/jmla.1998.2592

Pickering, M. J., & Ferreira, V. S. (2008). Structural priming: A critical review. *Psychological Bulletin, 134*(3), 427-459. doi: http://doi.org/10.1037/0033-2909.134.3.427

Pinheiro, J. C., & Bates, D. M. (2000). Linear mixed-effects models: basic concepts and examples. *Mixed-effects models in S and S-Plus*, 3-56. doi: https://doi.org/10.1007/0-387-22747-4_1

Rowland, C. F., Chang, F., Ambridge, B., Pine, J. M., & Lieven, E. V. M. (2012). The development of abstract syntax: Evidence from structural priming and the lexical boost. *Cognition, 125*(1), 49-63. doi: http://dx.doi.org/10.1016/j.cognition.2012.06.008

Rugg, M. D. (1985). The effects of semantic priming and word repetition on event-related potentials. *Psychophysiology, 22*, 642-647. doi: https://doi.org/10.1111/j.1469-8986.1985.tb01661.x

Savage, C., Lieven, E., Theakston, A., & Tomasello, M. (2003). Testing the abstractness of children's linguistic representations: lexical and structural priming of syntactic constructions in young children. *Developmental Science, 6*(5), 557-567. doi: http://doi.org/10.1111/1467-7687.00312

Segaert, K., Menenti, L., Weber, K., & Hagoort, P. (2011). A Paradox of Syntactic Priming: Why Response Tendencies Show Priming for Passives, and Response Latencies Show Priming for Actives. *PLoS One, 6*(10), e24209. doi: http://doi.org/10.1371/journal.pone.0024209

Smith, M., & Wheeldon, L. (2001). Syntactic priming in spoken sentence production – an online study. *Cognition, 78*(2), 123-164. doi: https://doi.org/10.1016/S0010-0277(00)00110-4

Thothathiri, M., & Snedeker, J. (2008). Syntactic priming during language comprehension in three- and four-year-old children. *Journal of Memory and Language, 58*(2), 188-213. doi: http://dx.doi.org/10.1016/j.jml.2007.06.012

Tomasello, M. (2000). Do young children have adult syntactic competence? *Cognition, 74*(3), 209-253. doi: https://doi.org/10.1016/S0010-0277(99)00069-4

Tooley, K. M., & Traxler, M. J. (2010). Syntactic priming effects in comprehension: a critical review. *Language and Linguistics Compass, 4*(10), 925-937. doi: http://doi.org/10.1111/j.1749-818X.2010.00249.x

Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science, 247*(4940), 301-306. doi: https://doi.org/10.1126/science.2296719

Weber, K., Christiansen, M. H., Petersson, K. M., Indefrey, P., & Hagoort, P. (2016). fMRI Syntactic and Lexical Repetition Effects Reveal the Initial Stages of Learning a New Language. *The Journal of Neuroscience, 36*(26), 6872-6880. doi: http://doi.org/10.1523/jneurosci.3180-15.2016

Weber, K., & Indefrey, P. (2009). Syntactic priming in German–English bilinguals during sentence comprehension. *NeuroImage, 46*(4), 1164-1172. doi: https://doi.org/10.1016/j.neuroimage.2009.03.040

Wiggs, C. L., & Martin, A. (1998). Properties and mechanisms of perceptual priming. *Current Opinions in Neurobiology, 8*(2), 227-233. doi: https://doi.org/10.1016/s0959-4388(98)80144-x

Wonnacott, E., Newport, E. L., & Tanenhaus, M. K. (2008). Acquiring and processing verb argument structure: Distributional learning in a miniature language. *Cognitive Psychology, 56*(3), 165-209. doi: https://doi.org/10.1016/j.cogpsych.2007.04.002

APPENDIX

Appendix A

Table 1. Example of one of the lists of lexical items. There were 8 such lists with different Alienese-to-English meaning mapping.

Alienese	**English**	**Dutch**
transitive verbs		
basi	to dress	aankleden
dase	to chase	achtervolgen
haki	to dry someone	afdrogen
kisu	to scare	bangmaken
momu	to serve	bedienen
mose	to hassle	bedreigen
nago	to greet	begroeten
nosoku	to pay	betalen
nuga	to jostle	duwen
oku	to photograph	fotograferen
omo	to help	helpen
ona	to interview	interviewen
sawe	to hug	knuffelen
sitagu	to massage	masseren
sosa	to tow	meetrekken
teso	to measure	meten
tomi	to call after	naroepen
tose	to make wet	natmaken
agero	to shoot	neerschieten

epaki	to topple	omtrekken
hakaro	to pick someone up	optillen
hakenu	to help getting up	overeindhelpen
hakoba	to annoy	pesten
hipare	to kick	schoppen
imera	to hit	Slaan
misabe	to tow	slepen
mukare	to stop	stoppen
nagabi	to draw	tekenen
nurasi	to console	troosten
odaku	to wave someone goodbye	uitzwaaien
odoka	to tie someone	vastbinden
odosi	to attend to someone	verzorgen
osuta	to find	vinden
sikimo	to feed	voeren
utape	to send away	wegsturen
utuso	to choke	wurgen
intransitive verbs		
atoku	to dry	afdrogen
mikuro	to yawn	gapen
parube	to bend over	buigen
simera	to dance	dansen
tokasi	to think	denken

mimu	to jump	hinkelen
ote	to cry	huilen
suki	to clap	klappen
ucha	to beckon	zwaaien
ugo	to drink	drinken
Nouns		
josa	woman	vrouw
komi	man	man
sako	boy	jongen
miru	girl	meisje

Table 2. Example sentences of the same content with the three different word-orders

Word-Order	**Alienese**	**Literal English translation**
Object Subject Verb	Josa komi oku.	* Woman man photograph.
Verb Object Subject	Oku josa komi.	* Photograph woman man.
Subject Verb Object	Komi oku josa.	* Man photograph woman.
Subject Verb	Miru simera	* Girl dance.

Table 3. Summary of fixed effects for the overall reading times over all days. The main contrasts of interests are marked in bold.

Predictor	**coefficient**	**SE**	**t-value**	**p-value**	
Intercept	2.44	0.04	54.57	<.001	***
Day (Day 3 vs. Day 9)	0.06	0.03	2.03	0.056	.
Day (Day 2 vs Day 3&9)	0.49	0.04	11.64	<.001	***
Syntax	**-0.03**	**0.01**	**-4.71**	**<.001**	*******
Verb	**-0.06**	**0.01**	**-11.07**	**<.001**	*******
Type of Sentence (Freq Vs. Infreq)	0.00	0.01	-0.05	0.965	
Type of Sentence (Known Vs. Novel)	0.02	0.01	2.03	0.047	*
Day (Day 3 vs. Day 9) * Syntax	**-0.01**	**0.01**	**-0.71**	**0.478**	
Day (Day 2 vs Day 3&9) * Syntax	**-0.01**	**0.01**	**-0.47**	**0.639**	
Day (Day 3 vs. Day 9) * Verb	0.01	0.01	0.42	0.672	
Day (Day 2 vs Day 3&9) * Verb	-0.03	0.01	-2.79	0.005	**
Syntax * Verb	**-0.02**	**0.01**	**-2.00**	**0.045**	*****
Day (Day 3 vs. Day 9) * Type of Sentence (Freq Vs. Infreq)	0.02	0.02	1.53	0.127	
Day (Day 2 vs Day 3&9) * Type of Sentence (Freq Vs. Infreq)	0.00	0.01	-0.05	0.961	
Day (Day 3 vs. Day 9) * Type of Sentence (Known Vs. Novel)	0.02	0.01	1.53	0.126	
Day (Day 2 vs Day 3&9) * Type of Sentence (Known Vs. Novel)	0.01	0.02	0.84	0.404	

Syntax * Type of Sentence (Freq Vs. Infreq)	**0.00**	**0.01**	**0.17**	**0.869**	
Syntax * Type of Sentence (Known Vs. Novel)	**0.00**	**0.01**	**-0.05**	**0.963**	
Verb * Type of Sentence (Freq Vs. Infreq)	-0.01	0.01	-0.74	0.461	
Verb * Type of Sentence (Known Vs. Novel)	0.02	0.01	2.10	0.036	*
Day (Day 3 vs. Day 9) * Syntax * Verb	**0.03**	**0.03**	**1.11**	**0.268**	
Day (Day 2 vs Day 3&9) * Syntax * Verb	**-0.01**	**0.02**	**-0.64**	**0.522**	
Day (Day 3 vs. Day 9) * Syntax * Type of Sentence (Freq Vs. Infreq)	**-0.01**	**0.03**	**-0.22**	**0.823**	
Day (Day 2 vs Day 3&9) * Syntax *Type of Sentence (Freq Vs. Infreq)	**-0.01**	**0.03**	**-0.23**	**0.816**	
Day (Day 3 vs. Day 9) * Syntax * Type of Sentence (Known Vs. Novel)	**0.00**	**0.03**	**-0.13**	**0.896**	
Day (Day 2 vs Day 3&9) * Syntax * Type of Sentence (Known Vs. Novel)	**0.00**	**0.03**	**0.17**	**0.863**	
Day (Day 3 vs. Day 9) * Verb * Type of Sentence (Freq Vs. Infreq)	-0.02	0.03	-0.71	0.479	
Day (Day 2 vs Day 3&9) * Verb *Type of Sentence (Freq Vs. Infreq)	0.02	0.03	0.77	0.444	
Day (Day 3 vs. Day 9) * Verb * Type of Sentence (Known Vs. Novel)	-0.01	0.03	-0.44	0.661	
Day (Day 2 vs Day 3&9) * Verb * Type of Sentence (Known Vs. Novel)	0.07	0.03	2.80	0.005	**
Syntax * Verb * Type of Sentence (Freq Vs. Infreq)	0.05	0.03	1.84	0.066	.
Syntax * Verb * Type of Sentence (Known Vs. Novel)	**-0.01**	**0.02**	**-0.46**	**0.643**	
Day (Day 3 vs. Day 9) * Syntax * Verb * Type of Sentence (Freq Vs. Infreq)	0.07	0.06	1.06	0.292	

Day (Day 2 vs Day 3&9) * Syntax * Verb * Type of Sentence (Freq Vs. Infreq)	-0.03	0.05	-0.62	0.535
Day (Day 3 vs. Day 9) * Syntax * Verb * Type of Sentence (Known Vs. Novel)	0.01	0.06	0.26	0.793
Day (Day 2 vs Day 3&9) * Syntax * Verb * Type of Sentence (Known Vs. Novel)	0.05	0.05	0.92	0.357

N= 14367 .<.1 *<.05, **<.01 ***<.001

Description of further effects not described in the main text:

Participants were slower on Day 2 than on the following days (β=.49, SE=.04, t=11.6, p<.001). This is partly due to the slightly different structure of the trials on Day 2 (see Methods). There was a main effect of Type of Sentence (β=.02, SE=.01, t=2.0, p=.047) as participants were slightly faster on the known compared to the new structures.

The verb repetition effect was larger on Day 2 than on the following days (β=-.03, SE=.01, t=-2.0, p=.005) as well as larger for the novel structures than for the known one (β=.02, SE=.01, t=2.1, p=.036), this might be driven by a stronger saliency for the verb, in either first or last position in the sentence for the new structures compared to the middle position for the known structure. This stronger verb repetition effect for the novel structures was mainly present on Day 2 as evidenced by a three-way interaction between Day, Verb and Type of Sentence (β=.07, SE=.03, t=2.8, p=.005).

Table 4. Summary of fixed effects for the overall reading times on Day 2. The main contrasts of interests are marked in bold.

Predictor	**coefficient**	**SE**	**t-value**	**p-value**	
Intercept	2.77	0.06	45.25	<0.001	***
Syntax	**-0.01**	**0.01**	**-2.62**	**0.009**	****
Verb	**-0.04**	**0.01**	**-7.14**	**<0.001**	*****
Type of Sentence (Freq Vs. Infreq)	0.00	0.01	-0.08	0.941	

Type of Sentence (Known Vs. Novel)	0.03	0.02	1.71	0.089	.
Syntax * Verb	**-0.01**	**0.01**	**-1.46**	**0.144**	
Syntax * Type of Sentence (Freq Vs. Infreq)	**0.00**	**0.01**	**-0.02**	**0.985**	
Syntax * Type of Sentence (Known Vs. Novel)	**0.00**	**0.01**	**0.21**	**0.832**	
Verb * Type of Sentence (Freq Vs. Infreq)	0.00	0.01	0.13	0.895	
Verb * Type of Sentence (Known Vs. Novel)	0.04	0.01	2.92	0.004	**
Syntax * Verb * Type of Sentence (Freq Vs. Infreq)	0.01	0.01	0.56	0.577	
Syntax * Verb * Type of Sentence (Known Vs. Novel)	**0.01**	**0.01**	**0.40**	**0.692**	

N= 5645 .<.1 *<.05, **<.01 ***<.001

Description of further effects not described in the main text:

The interaction between Type of Sentence (known versus new) and Verb (β=.04, SE=.01, t=2.9, p=.004), is due to participants showing a larger verb repetition effect for the new structures. This might be driven by a stronger saliency for the verb, in either first or last position in the sentence for the new structures compared to the middle position for the old structures.

Table 5. Summary of fixed effects for the response choices on Day 3 and 9. The main contrasts of interests are marked in bold.

Predictor	**Coefficient**	**SE**	**Wald Z**	**p-value**	
Intercept	2.12	0.16	13.23	<.001	***
Day	0.61	0.23	2.64	0.01	**
Verb	**0.24**	**0.06**	**3.82**	**<.001**	*******
Syntax	**0.38**	**0.07**	**5.43**	**<.001**	*******
Type of Sentence (Freq Vs. Infreq)	-0.13	0.10	-1.41	0.16	
Type of Sentence (Known Vs. Novel)	0.04	0.17	0.23	0.82	
Day*Verb	0.23	0.13	1.85	0.06	.
Day*Syntax	**-0.39**	**0.13**	**-2.95**	**<.001**	******
Verb*Syntax	**0.23**	**0.13**	**1.83**	**0.07**	**.**
Day*Type of Sentence (Freq Vs. Infreq)	-0.24	0.17	-1.41	0.16	
Day*Type of Sentence (Known Vs. Novel)	-0.20	0.16	-1.26	0.21	
Verb*Type of Sentence (Freq Vs. Infreq)	-0.08	0.15	-0.49	0.62	
Verb*Type of Sentence (Known Vs. Novel)	0.23	0.13	1.71	0.09	.
Syntax*Type of Sentence (Freq Vs. Infreq)	**0.32**	**0.15**	**2.07**	**0.04**	*****
Syntax*Type of Sentence (Known Vs. Novel)	**0.36**	**0.14**	**2.56**	**0.01**	*****
Day*Verb*Syntax	**-0.52**	**0.25**	**-2.06**	**0.04**	*****
Day*Verb*Type of Sentence (Freq Vs. Infreq)	-0.39	0.31	-1.26	0.21	
Day*Verb*Type of Sentence (Known Vs. Novel)	-0.16	0.27	-0.59	0.55	
Day*Syntax*Type of Sentence (Freq Vs. Infreq)	**0.29**	**0.31**	**0.96**	**0.34**	

Day*Syntax*Type of Sentence (Known Vs. Novel)	**-0.02**	**0.27**	**-0.08**	**0.94**	
Verb*Syntax*Type of Sentence (Freq Vs. Infreq)	0.39	0.31	1.28	0.20	
Verb*Syntax*Type of Sentence (Known Vs. Novel)	**0.98**	**0.27**	**3.64**	**<.001**	*******
Day*Verb*Syntax*Type of Sentence (Freq Vs. Infreq)	0.47	0.61	0.77	0.44	
Day*Verb*Syntax*Type of Sentence (Known Vs. Novel)	0.89	0.54	1.66	0.10	.

N= 10290

.<.1 *<.05, **<.01 ***<.001

Description of further effects not described in the main text:

Participants improved in making the correct choice from Day 3 to Day 9 (β=.61, SE=.23, Z=2.64, p=.01).

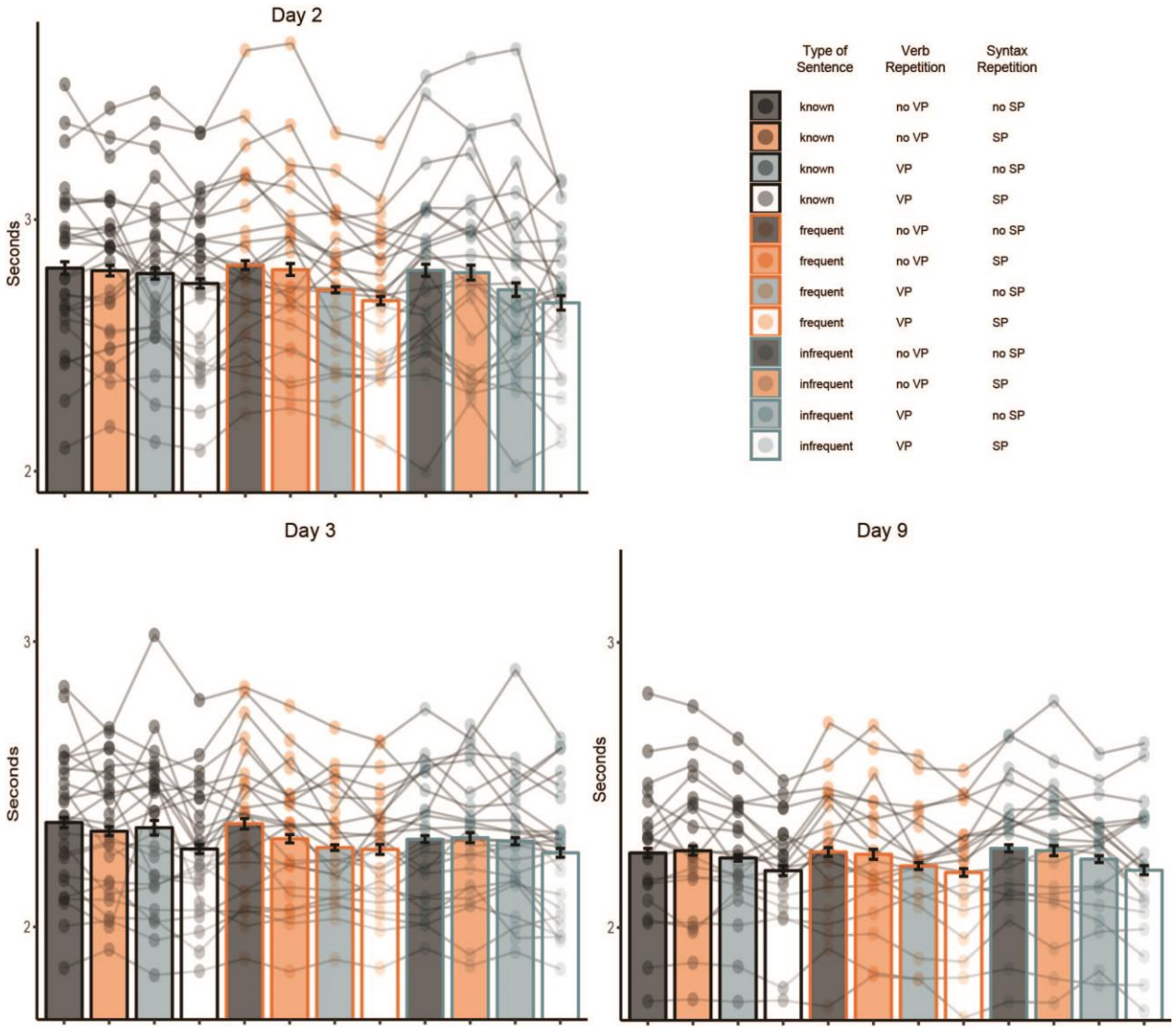

Figure 1. Total reading times per day and condition. The error bars show the standard error of the mean. Dots and lines represent individual subjects' performance.

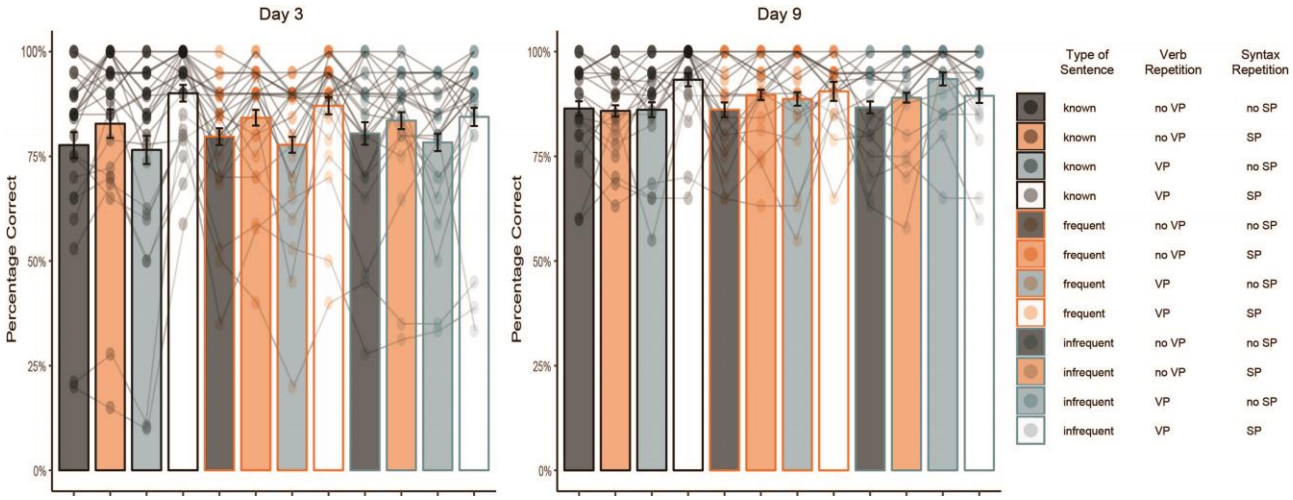

Figure 2. Response choices per day and condition. The error bars show the standard error of the mean. Dots and lines represent individual subjects' performance.