# Bilingual syntax as implicit learning

Yung Han Khoe

Centre for Language Studies

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# Bilingual syntax as implicit learning

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# Bilingual syntax as implicit learning

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# Contents

# 1
# General introduction

## 1.1 Introduction

When we hear or read language, we have an expectation of the words that will come up. Our expectation of upcoming words is based on the words that we have heard or read before. This thesis refers to a concrete expectation as a *prediction*. If our prediction turns out to be incorrect, this results in a *prediction error*. That happens, for example, with sentences such as ”Our expectation of upcoming words is based on the words that we have heard never.” or ”Our expectation of upcoming words is based on the words that we before heard have.” In the first example, the word ”*never*” is not what we predicted in terms of its meaning. In the second example, the words ”*before heard have*” are unexpected because of the ordering of the words, or *syntax*, in the sentence.

How we order words in sentences can be described declaratively as a set of rules and regularities or it can be regarded as procedural knowledge or ability. This distinction has been a matter of debate in linguistics for a long time (e.g., Jackendoff, 2007; Newmeyer, 2000). This thesis studies how we order words in sentences as procedural knowledge or ability. We use this syntactic ability when we produce a sentence, but also when we hear a sentence and we are predicting what words will come up. As such, this thesis is a work of psycholinguistics (or psychology of language). The psychological nature of the work means that it investigates how *people* order words in sentences as a mental process, rather than studying how words are ordered in sentences as a property of language. The claim of this thesis (and of the work on which it builds) is that prediction error in sentence processing leads to *implicit learning* and that this learning process can explain aspects of how we acquire and use language (e.g., structural priming), even when they might not, at first glance, seem to be related to learning. This claim is tested in this thesis using cognitive computational models that instantiate implicit learning (see Section 1.2).

An important test for any psycholinguistic theory is whether it holds up for people who speak more than one language. A bilingual's language system does not consist of two separate and independent monolingual language systems (Grosjean, 1989). Instead, the two languages in a bilingual system can interact in acquisition, and in processing and production. There is no shortage of evidence for such cross-linguistic influence in research on bilingual acquisition (Chantal et al., 2022; Serratrice, 2013). Also, cross-language structural priming (Hartsuiker, Pickering, & Veltkamp, 2004), the phenomenon that bilinguals are more likely to produce a sentence structure in one language when they have recently encountered that structure in their other language, is a well established bilingual phenomenon that connects processing and production in a bilingual's language system. Even more clearly, the seemingly effortless ability of many bilinguals to use both languages in a single sentence, intra-sentential code-switching (Poplack, 1980), shows how two languages can interact in bilingual language production. To gain further insight into these phenomena, this thesis investigates syntax as implicit learning specifically in people who use more than one language. The next paragraph and Chapter 2 introduce the cognitive models used in these investigations. Section 1.3 gives an overview of the bilingual phenomena that are simulated using those models in this thesis. Some of these phenomena, such as cross-language structural priming, have already been linked theoretically to implicit learning in the literature (e.g., Hartsuiker, Beerts, Loncke, Desmet, & Bernolet, 2016; van Dijk & Hopp, 2025), whereas this is less so for others, such as processing of code-switches.



## 1.2 Cognitive neural network models of language

Cognitive models, such as the ones used in this thesis, instantiate a theory about a mental process. They implement a mechanism that is hypothesized to underlie such a process. A *connectionist* cognitive model implements a mental process using a network of interconnected units, the nodes or neurons. The nodes in the network are grouped into layers. During prediction, activation spreads through the network from the input layer, via intermediate layers, such as hidden or compress layers, to the output layer. How activation spreads through the network depends on the strength of the connections between individual nodes, the *connection weights*.

Connectionist models are either *localist* models or *distributed* models, commonly referred to as neural network models or Artificial Neural Networks (ANNs). Several of the most influential cognitive models in bilingualism research are localist models (e.g., Dijkstra & van Heuven, 1998, Dijkstra et al., 2019). The nodes in such localist models have discrete interpretations and the connection weights in these models are set by hand. In contrast, neural network models of language can learn about syntax by being *trained* on language input, including bilingual language input (e.g., Filippi, Karaminis, & Thomas, 2014; P. Li & Farkaš, 2002; Tsoukala, Broersma, Van Den Bosch, & Frank, 2021). The models predict sentences word-by-word. When prediction error occurs, connections in the model are updated through an error-based learning algorithm called backpropagation (Rumelhart, Hinton, & Williams, 1986). Generally, the input that the models learn from consists of a set of sentences, and the models iterate over that set multiple times. One such iteration is called an *epoch*. See Frank, Monaghan, and Tsoukala (2019) for a review of work on language processing and acquisition using neural network models.

The core architecture of the models in this thesis is that of a simple recurrent network (SRN; Elman, 1990, Elman, 1991). The recurrence in this model enables it to learn from the previous words in a sentence when predicting the next word. The (Bilingual)

Dual-path model used in this thesis extends the SRN architecture to learn not just from sentences but also semantic messages that the sentences express (see Chapter 2). The models in this thesis instantiate an error-based implicit learning account of a range of findings in the psycholinguistics of bilingualism.

## 1.3 Thesis outline

**Chapter 2** discusses the Bilingual Dual-path model, which is used for the simulated experiments in the following chapters. The chapter first introduces the original, monolingual Dual-path model. It then provides a methodological review of the cognitive modeling work on syntactic transfer, bilingual acquisition and code-switching that has been done using the Bilingual Dual-path model.

**Chapter 3** presents simulated cross-language structural priming experiments, using the Bilingual Dual-path model, that test: (1) whether error-driven implicit learning can explain priming between different languages, (2) whether this account allows for priming between structures with different word order, (3) whether cross-language and within-language priming are equally strong under this account, and (4) whether the account predicts structural priming between languages that are not closely related.

**Chapter 4** explores whether proficiency or exposure affect the cross-language priming effect (that was found in the previous chapter) in simulated simultaneous bilinguals.

The Dual-path model has not only been used as a sentence production model. A version of the model has also been developed to simulate event related potentials (ERPs) in sentence processing. In **Chapter 5** this model is extended to bilingual sentence processing. The chapter investigates whether the model can account for how ERPs in response to syntactic violations in second-language learning develop during learning, and simulates the influence of cross-language similarity on such ERPs.

**Chapter 6** brings together the bilingual phenomena of code-switching and cross-language structural priming. It reports on whether structural priming from Spanish to English increases with code-switching in the prime sentences, in the model and in

Spanish-English bilinguals from the US.

Finally, **Chapter 7** concludes the thesis by summarizing the findings, presenting theoretical implications, and discussing directions for further research.

# 2

# The Bilingual Dual-path model

**Based on the abstract and sections 1, 2, 3.1, 3.2 and 3.4 of:** Khoe, Y. H., & Frank, S. L. (2024). The Bilingual Dual-path model: Simulating bilingual production, processing, and development. *Linguistic Approaches to Bilingualism*.

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## Abstract

Experimental research has yielded many important psycholinguistic findings in bilingualism, while cognitive computational models of sentence processing were limited to the single-language case until recently. In this chapter, we discuss cognitive modeling work that uses the Bilingual Dual-path model to simulate experimental research on bilingual sentence production, processing and development.

## 2.1 Introduction

Over the last decade, behavioral experimental research in bilingual sentence processing has yielded a considerable body of work with many important psycholinguistic findings. Often, however, the mechanisms that underlie these effects remain unclear. Cognitive computational models can play an important role in investigating these mechanisms, as is the case for effects in monolingual psycholinguistics (e.g., Ryskin & Nieuwland, 2023, recently argued for this with regards to prediction in language processing). Until recently, the computational cognitive models of sentence processing that did exist were limited to the single-language case (Frank, 2021). We review advances in extending cognitive modeling to bilingual sentence production using the Bilingual Dual-path model (Janciauskas & Chang, 2018; Tsoukala, Broersma, et al., 2021) that has been used to simulate a range of findings in the psycholinguistics of bilingualism. The investigated phenomena range from pronoun gender errors in Spanish-English bilinguals (Tsoukala, Frank, & Broersma, 2017) to event-related potential (ERP) effects in L2 learners (see Chapter 5).

A distinctive feature of studies using the (Bilingual) Dual-path model, compared to many other cognitive modeling studies, is that individual model instances are trained, thereby simulating a sample of individual participants. These simulated participants vary in similar ways as a sample of human participants in terms of, for example, proficiency. This contrasts with the more common practice of fitting a model to data averaged over individuals. Because the studies that we review use model instances as simulated participants, these studies use statistical methods (e.g., mixed effects models, see Section 2.3.2) that are essentially the same as those used in experimental studies. These modeling studies also show a similar evolution towards the use of current methods and best practices such as preregistration and Bayes Factor analysis (see Chapter 3).

Simulating experiments with Dual-path has three major advantages over human experiments or simulations using other cognitive models (see Frank et al. (2019) for a review of other work on language processing and acquisition using neural network models). Firstly, to isolate the causal role of syntactic properties of a language, different versions of the language the model learns can be created that differ only in one specific property of interest. In Chapter 3, for example, we use a version of Dutch with verb-final passives and another with verb-medial passives, to test whether cross-language structural priming requires two languages with identical word order for the syntactic constructions involved.

Secondly, characteristics of simulated participants can be manipulated. For instance, Tsoukala, Broersma, et al. (2021) simulated the differences in code-switching behavior between simultaneous and sequential bilinguals. They trained two sets of models (i.e., simulated participants) with the same model architecture and input languages, but whereas one set of models learned both languages from the start, the other models only started learning the L2 after learning the L1.

Thirdly, experimental designs are possible that are not practically feasible with humans. In Chapter 5, we hypothesize that a simulated P600 ERP effect, in response to a syntactic violation in the L2, would increase as learning of that L2 progressed. This is commonly tested in humans using a between-participant design (e.g., Tanner, McLaughlin, Herschensohn, & Osterhout, 2013), although longitudinal studies with a limited number of experimental sessions exist (e.g., Soskey, Holcomb, & Midgley, 2016). In our simulations, however, a within-participants design is implemented to test for the P600 effect at many consecutive learning stages.

We first introduce the (monolingual) Dual-path model. We then discuss the Bilingual Dual-path model and review the work that has been done to date with that model.

## 2.2 The Dual-path model

When people learn how to produce a language, this involves learning how to map from a set of ideas to a sequence of words. Similarly, the Dual-path model learns mappings from messages to sentences. After training, the model can therefore receive a message and then produce a sentence that expresses this message. Because of this, the Dual-path is a model of sentence production and can be used to simulate experiments in which participants produce sentences. Also, the model can be applied to simulate effects found in language comprehension experiments (See Section 2.2.4).



### 2.2.1 Model architecture and training

The Dual-path model was originally proposed to address the critique that (recurrent) neural networks (see Section 1.2) cannot generalise in the same way as people (Chang, 2002). While people can learn to generalise equivalence relations such as "*an X is an X*" from sentences like "*A rose is a rose*" or "*A bike is a bike*", an SRN could not (Marcus, 1998). Even though it could learn equivalence sentences, it could not generalise to such sentences with novel words: It did not predict that the next word in the sentence: "*a blicket is a* ..." should be "*blicket*". This inability to generalise to abstract variable-based frames such as "*an X is an X*", called symbolic generalisation, is an important limitation of neural networks as models of acquisition and production of syntax.

To achieve human-like symbolic generalisation, the sentences that form Dual-path's training input are paired with *messages* and the model extends the SRN's architecture with a meaning pathway to learn from these messages. A message consists of concepts (e.g., "WOMAN" or "BIKE") that are bound to their semantic roles (e.g., "X" or "ACTION-LINKING") and also includes event semantics. For instance, "*the bottle is broken by the father* ." expresses the message "X = def, FATHER; ACTION-LINKING = BREAK; Y = def, BOTTLE; EVENT-SEM = PAST, SIMPLE, ACTION-LINKING". In the meaning pathway, Dual-path learns to map the message to words. At the same time, it learns how to order these words in the sequencing pathway, the model's SRN part. In this way, the model finds a balance between symbolic learning in the meaning pathway and statistical learning in the sequencing pathway.

In addition to a human-like ability to balance symbolic and statistical learning, simulations of double dissociations in patients with aphasia[1] also provide support for the model's dual-pathway architecture. Chang (2002) created two models with different

[1]Some patients with aphasia experience more difficulty with function words than with content words, while others show the reverse pattern. This is called the function-content word dissociation. A similar dissociation between heavy verbs and light verbs has also been reported. Gordon and Dell (2002) have argued that this double dissociation pattern reflects underlying differences between how syntax and semantics are represented.

types of impairments by lesioning each pathway, that is, by removing weights between random sets of units in that pathway. These models produced sentences with double dissociations similar to those produced by people with aphasia.

Training the Dual-path model requires corpora that consist of sentences and their meaning representations, which are not (widely) available[2]. The model is therefore trained on a small artificial language, generated from a simplified grammar and lexicon, making it relatively easy to systematically manipulate input language properties. A disadvantage is that such an artificial language can contain sentences that are not "meaningful" when the sentence generator lacks sufficient world knowledge to ensure that they are. For example: a sentence such as "the dog plugs the bath with beer" is equally likely to occur in the artificial language as "the waiter fills the cup with coffee" (for details, see Chang et al., 2006).

### 2.2.2 Structural priming

Arguably the most influential application of Dual-path was to model structural (or syntactic) priming. When people have a choice between two alternative syntactic structures to express the same meaning (e.g., active vs. passive and prepositional object vs. double object datives), they tend to produce recently heard or produced structures (Bock, 1986). For instance, someone can either say "*The man showed a dress to the woman*", using a prepositional dative, or "*The man showed the woman a dress*", using a double-object dative, to describe the same event. After hearing a prepositional dative such as "*The governess made tea for the princess*", they are more likely to also produce that structure.

Typical structural priming experiments use a comprehension-to-production prim-

[2] Corpora with semantic annotations exist, but cover a limited range of languages and syntactic phenomena. The format of those annotations would have to be made compatible with Dual-path. The most unusual aspect of Dual-path's meaning representation is its 'XYZ' format which uses identical roles for intransitive agents and transitive patients. Chang, Dell, and Bock (2006) developed the XYZ role representation by testing several representational schemes. In their simulations, the XYZ role representation made the right prediction about the development of the intransitive construction in preferential-looking studies whereas the traditional-role representation did not. However, the XYZ format is not required for structural priming in the model (see Section 2.2.2). The work required to make an existing corpus compatible with Dual-path depends on the specifics of that corpus and the language phenomenon under investigation.

ing paradigm in which participants hear a prime sentence before producing a target sentence. To simulate such experiments, instances of Dual-path are trained to function as simulated participants. In simulated priming experiments, the model instances first process a prime sentence, without a message, after which a message that can be expressed with two alternative structures elicits a target sentence from the model. If the model's next-word predictions for the prime correspond to a syntactic structure that differs from the prime's, prediction error occurs. The model's connection weights are then adjusted, such that next-word predictions will more strongly tend to follow the prime's structure. This implies an increased probability of producing that structure, since one and the same network predicts while processing the prime and produces sentences. This increased probability of production shows up as structural priming in simulated experiments. Thus, Dual-path explains structural priming as the result of error-driven implicit learning, in contrast with accounts that characterise structural priming as resulting from short-lived residual activation (e.g., Pickering & Branigan, 1998). Simulated experiments show that Dual-path has the same tendency as people to reuse recently encountered syntactic structures in English (Chang et al., 2006) and in German (Chang, Baumann, Pappert, & Fitz, 2015). Since Dual-path does not actually model comprehension (it does not map a prime sentence to a meaning representation), this correspondence between simulated and behavioral results suggests that structural priming might be more accurately referred to as a processing-to-production than a comprehension-to-production phenomenon.

### 2.2.3 Acquisition

Dual-path is not just a model of sentence production but also of syntax acquisition. Because the model learns to produce sentences by processing the training input sentence-by-sentence, the model's sentence production can be tested at any stage of syntactic development. In this way, the model has been used in several simulations of acquisition in English that involve: transitives with novel verbs (e.g., "*Marty is glorping Mary.*"; Chang et al., 2006), relative clauses (e.g., "*The cat that the dog chased climbed the tree.*"; Fitz, Chang, & Christiansen, 2011), the locative alternation (e.g., "*The man sprayed* *water on the wall.*" vs. "*The man sprayed the wall with water.*"; Twomey, Chang, & Ambridge, 2013), and auxiliary inversion (e.g., deriving "*Is the boy that is jumping happy?*" from "*The boy that is jumping is happy.*"; Fitz & Chang, 2017). Also, it has been used to compare the acquisition of word-order phenomena, such as heavy noun-phrase shift (e.g., that the word order in "*I gave to Mary the book that I bought last week.*" is acceptable, while it is strongly dispreferred in "*I gave to Mary the book.*") in English and Japanese (Chang, 2009).

### 2.2.4 The comprehension process

Strictly speaking, Dual-path is not a model of sentence comprehension since it does not learn how to produce a meaning representation from a sentence. Nevertheless, the model has proven to be useful in simulating the comprehension process. As discussed above, the model simulates structural priming. While structural priming is sometimes thought of as a language production phenomenon, the typical structural priming experiment has a comprehension-to-production structure (although comprehension-to-comprehension priming experiments have also been conducted, as well as comprehension-and-production-to-production experiments in which participants had to repeat the prime sentences), in which participants hear a prime sentence and then produce a target sentence. This means that Dual-path can simulate an aspect of comprehending the prime sentence that is responsible for structural priming in producing the target sentence, namely the prediction carried out by the production system and the subsequent learning in that system (Dell & Chang, 2014).

Fitz and Chang (2019) characterise the mechanism underlying structural priming as a linguistic adaptation process in the sentence production system that occurs during sentence comprehension. They propose that this same process is reflected in ERP signals that have typically been interpreted as reflecting language comprehension. Fitz and Chang (2019) adapted Dual-path to provide an implicit learning account of such ERPs. In this account, ERPs arise from brain activity that reflects how prediction error propagates through a person's language system during comprehension. Error propagation reaches the lexical-semantic system first, where it can lead to an N400 effect, before propagating to the syntactic system, where it can lead to a P600 effect. In Dual-path, therefore, the N400 is modelled by measuring prediction error at the lexical layer, the model's output layer, and the P600 is modelled in the same way from back-propagated prediction error at the sequencing layer, the hidden layer in the model. Fitz and Chang (2019) successfully simulated a range of electroencephalography (EEG) experiments that studied N400 effects in response to semantic violations and P600 effects in response to syntactic violations.

## 2.3 The Bilingual Dual-path model

The Dual-path model has proven to be useful in investigating the underlying mechanisms of syntactic processing in a single language. The model not only simulates phenomena in production and comprehension, but can also simulate their acquisition. After developing a bilingual version of the model, this makes Dual-path particularly useful in uncovering psycholinguistic mechanisms when more than one language is involved. Even more than is the case for a monolingual's language system, production and comprehension in bilinguals can rarely be understood without considering acquisition. This is clear, for example, in how cross-language structural priming and ERP effects interact with L2 proficiency (see Chapters 4 and 5). Here we discuss how such phenomena have been investigated using the *Bilingual* Dual-Path model.

Tsoukala et al. (2017) and Janciauskas and Chang (2018) independently developed bilingual versions of Dual-path (Figure 2.1). Both studies extended the monolingual model by adding word units for a second language to the input and output layers, and by using a target language node as an additional input to the hidden layer. Except for the application by Janciauskas and Chang (2018), all applications of Bilingual Dual-path reviewed here and that we are aware of, use (adaptations of) the implementation by Tsoukala et al. (2017).

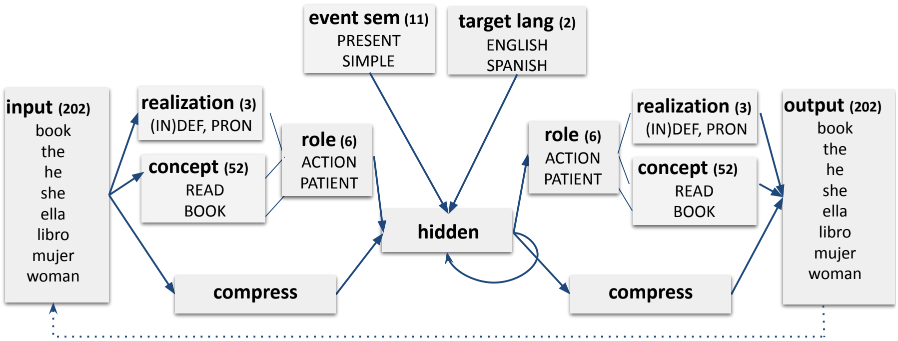


**Figure 2.1:** Spanish-English Bilingual Dual-path model architecture. The syntactic path is in the figure's lower part, via the "compress" layers. The semantic path, in the upper part, contains information about concepts and their realization, and thematic roles. Numbers in parentheses indicate layer sizes, which vary across model instances for hidden and compress layers. Solid arrows indicate trainable connection weights. Lines between roles, realization, and concepts denote connections that are given as part of the message. The dotted arrow indicates that a word the model produces is given back as input for the next word. (Figure reproduced from Tsoukala, Broersma, et al., 2021)

### 2.3.1 Syntactic transfer

Tsoukala et al. (2017) developed a Spanish-English version of the Dual-path model to study gender pronoun errors that L1 Spanish speakers make in L2 English. These L2 learners sometimes confuse the two singular nominative pronouns, referring to an actress as 'he' or a father as 'she' (Lahoz, 1991). This is unexpected, since Spanish has equivalent male and female pronouns and morphologically separates the genders more than English does (Tsoukala et al., 2017).

The study hypothesized that speakers of Spanish make these errors because Spanish is a pro-drop language while English is not (Lahoz, 1991). To isolate the effect of the pro-drop feature, Tsoukala et al. (2017) created two versions of Spanish that differed only in having this feature or not. To simulate late L2 learning, they first trained models with Spanish input only, before continuing with bilingual Spanish-English input. A hundred sets of initial random weights were generated to form the basis of 100 pairs of model instances, where each pair was trained using each different versions of Spanish. Confirming the hypothesis, the results revealed that model instances trained using pro-drop Spanish produced more gender errors than those trained using Spanish without pro-drop. This shows that the surprising gender pronoun errors can be explained as resulting from L1 transfer. It also demonstrates how Bilingual Dual-path can be used to validate linguistic hypotheses in a way that is impossible using human experiments.



### 2.3.2 Bilingual acquisition

While (second) language acquisition obviously requires linguistic input, several studies have shown that knowledge of L2 grammar rules does not seem to improve with more language exposure (e.g. Flege, Yeni-Komshian, & Liu, 1999). Janciauskas and Chang (2018) reanalysed data from a grammaticality judgement study by Flege et al. (1999) to examine this issue. That study did find that performance of Korean learners of L2 English on English grammaticality judgement tasks decreased as age of L2 acquisition (AoA) increased, but it did not find an effect of length of L2 exposure (LoE). Whereas Flege et al. (1999) analysed performance on each grammar rule using separate ANOVAs, Janciauskas and Chang (2018) included grammar rule as a predictor to factor out rule variation in a logistic mixed-effects model that also factored out participant and test item variation. The reanalysis revealed better L2 performance with increased length of L2 exposure and how this differed between grammar rules. However, a negative interaction between AoA and LoE showed late learners benefiting less from a longer LoE than early learners. A weaker effect of LoE in late learners depended on grammar rule frequency. More frequent rules were impacted more than less frequent rules. In other words, for more frequent grammar rules, the effect of LoE was larger in early than in late learners. For less frequent grammar rules, this difference in LoE effect size was less pronounced. Janciauskas and Chang (2018) suggest that this shows that late learners are unsuccessful in using higher frequency of rules to learn them better.

Janciauskas and Chang (2018) then investigated whether the learning mechanism of Dual-Path could explain the reanalysis' findings. They developed a Korean-English bilingual Dual-path model. The artificial versions of Korean and English for this model had five grammar rules with different frequencies, reflecting the frequencies of those rules in a corpus. To simulate L2 learning, the model received training input in Korean only first, before receiving input that was half in English and half in Korean. The amount of initial training in Korean only was varied to simulate groups of participants with different L2 English AoAs. Simulations were conducted with 10 model instances for each AoA group. The results were analysed using mixed-effects models that account for variation between model instances in the same way as for individual differences in humans. The analysis revealed a pattern of effects of AoA, LoE, and rule frequency that matched what the reanalysis found, which indicates that an implicit learning model can account for those findings. However, as was noted by Frank (2021), a "critical period" was built into the model by gradually decreasing the learning rate (a parameter that scales connection weight update in backpropagation) in the syntactic pathway in a way that was not done for earlier monolingual models. Unlike in those models, separate learning rates were used for the lexical and syntactic paths in the model that varied independently, with the syntactic learning rate reducing to 0 at the end of learning.

### 2.3.3 Code switching

Code switching is the alternation in bilingual speech from one language to the other, between or within sentences. Tsoukala, Broersma, et al. (2021) adapted Bilingual Dual-path to investigate this phenomenon.[3] Before producing the first word of a sentence, only one target-language unit was activated to bias the model towards producing a word in that language. After the first word, both target-language units were equally activated to allow the model to code-switch. These simulations were conducted with 40 model instances. For increased generalisability, each model instance was trained on a different set of randomly generated message-sentence pairs. Also, a number of free parameters differed across model instances.

[3] Tsoukala, Frank, Van Den Bosch, Valdés Kroff, and Broersma (2019) presented an earlier version of the code-switching model.

Simulations showed that the model produced sentences with code switches, even though code switches did not occur in the languages used to train the model, which is in line with claims from Lederberg and Morales (1985) that bilinguals do not need (extensive) exposure to code-switched language to code switch themselves[4].

The simulations also compared simultaneous to sequential bilingual models. While the simultaneous models were trained on both languages (roughly 50% per language) for 40 epochs, the sequential models were trained on only one language for about 15 of 40 epochs before receiving input in both languages for the remaining epochs. An analysis of the sentences these models produced showed that simultaneous models code-switched much more often than sequential models, in line with how bilinguals reportedly code switch (e.g., Gollan & Ferreira, 2009).

In another study, Tsoukala, Frank, Van Den Bosch, Valdés Kroff, and Broersma (2021) investigated why Spanish-English bilinguals are more likely to code-switch after the Spanish auxiliary verb "*estar*" ("*to be*") than after the auxiliary "*haber*" ("*to have*") and the following participle (a phenomenen known as the auxiliary phrase asymmetry). The simulations tested the hypothesis by Tamargo, Valdés Kroff, and Dussias (2016) that the asymmetry occurs because "*estar*" has more semantic weight than "*haber*" since it also occurs as an independent verb, for instance in "*la niña está cansada*" ("*the girl is tired*"), while "*haber*" does not.

Two artificial versions of Spanish were created for this study. The first one, the "*haber*" version, had the difference in semantic weight between "*estar*" and "*haber*". In contrast, the second "*tener*" version, was manipulated to have equal semantic weight for the two verbs, by replacing all instances of "*haber*" with "*tener*". Therefore, this second version of Spanish had a verb "*tener*" that, similar to "*to have*" in English, occurred both as main and auxiliary verb, while only occurring as auxiliary verb in the "*haber*" version. This was the only difference between the two language versions. Identical simulations were conducted with 60 model instances for each version. Model instances differed from each other due to slight variation in the balance between Spanish and English in the input, randomization of most free model parameters, the use of

[4] See Tsoukala (2021) for a discussion on how Bilingual Dual-path compares to other cognitive models of code-switching such as the Control Process Model of code-switching (CPM; Green & Wei, 2014).

different randomly generated training input, and random initialization of connection weights before training.

A similar asymmetric code-switching pattern as Spanish-English bilinguals produce, occurred in the simulations using the "*haber*" language version, but not the "*tener*" one. This indicates that the auxiliary verb's lack of semantic weight "*haber*" can cause the auxiliary phrase symmetry in code switching.

## 2.4 Conclusion

We have reviewed how the Bilingual Dual-path model has contributed to the methods in bilingualism research. To shed light on underlying mechanisms, the model has been used to simulate a range of experimental findings. These simulations demonstrate that several phenomena in bilingual sentence processing can be explained by an error-driven implicit learning account. We extend this work in the following chapters by simulating cross-language structural priming (Chapter 3, 4 and 6), ERPs in L2 learning (Chapter 5), and processing of code-switches (Chapter 6).

# 3

# Is structural priming between different languages a learning effect? Modelling cross-language structural priming as error-driven implicit learning

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## Abstract

To test whether error-driven implicit learning can explain cross-language structural priming, we implemented models of bilingual sentence production for four different language pairs: Spanish – English, verb-final Dutch – English, verb-medial Dutch – English, and Indonesian – verb-medial Dutch. With these models, we conducted simulation experiments that all revealed clear and strong cross-language (and within-language) priming effects.

One of these experiments included structures with different word order between the two languages. This enabled us to distinguish between the error-driven learning account of structural priming and an alternative hybrid account which predicts that identical word order is required for cross-language priming. Cross-language priming did occur in our model between structures with different word order. This is in line with results from behavioural experiments.

The results of the experiments reveal varying degrees of evidence for stronger within-language priming than cross-language priming. This is consistent with results from behavioural studies.

Overall, our findings support the viability of error-driven implicit learning as an account of cross-language structural priming.

## 3.1 Introduction

### 3.1.1 Structural Priming



Structural priming is the tendency of speakers to reuse syntactic structures that they have previously encountered. In the study by Bock (1986) that introduced structural priming as an experimental paradigm, participants were more likely to use a passive target sentence (e.g., "*The church is being struck by lightning*") after hearing and then repeating a passive sentence ("*The referee was punched by one of the fans*") than after repeating an active prime sentence ("*One of the fans punched the referee*"). If one sentence structure primes another, even without lexical overlap between the two sentences, then these sentences share some structural aspect of their mental representation.

Structural priming is not only a real-life discourse phenomenon that speakers use to adapt to their dialogue partners linguistically, but also forms a research tool: Careful investigation of the structural relations between sentences that prime each other has provided insight into syntactic representations without relying on speakers' explicit notions of grammaticality (Branigan & Pickering, 2017). Structural priming also occurs between different languages (Hartsuiker et al., 2004; Huttenlocher, Vasilyeva, & Shimpi, 2004; Meijer & Fox Tree, 2003). Investigating these cross-language priming effects can give insight into how syntactic representations in different languages relate to each other in multilingual speakers.

One of the proposed accounts of within-language structural priming is error-driven implicit learning. This account has been implemented in the Dual-path model of sentence production (see Section 2.2) (Chang et al., 2006). To verify whether error-driven implicit learning can also account for cross-language priming, we implement three different bilingual Dual-path models, and we test whether these models can simulate results from behavioural priming experiments.

#### 3.1.1.1 Error-driven implicit learning accounts of structural priming

According to an implicit learning account of structural priming (Chang, Dell, Bock, & Griffin, 2000; Chang et al., 2006), error-driven learning causes changes in the extent to which different syntactic structures are expected to occur. In this account, upcoming words are predicted during sentence comprehension. When a word is predicted incorrectly during the processing of a prime sentence, this prediction error is used to strengthen the connections associated with the prime's syntactic structure, which makes that structure's occurrence more expected. This learning mechanism affects the production of the target sentence as it increases the likelihood of producing the same structure. In this account, structural priming is therefore regarded as a long-lasting and cumulative effect. The same error-driven learning mechanism that is responsible for syntax acquisition is also responsible for structural priming in this account.

Support for this view on structural priming has been provided in a large number of studies that have demonstrated that this type of priming can last over time and persists over the processing of other sentences, both in within-language priming (Bock & Griffin, 2000; Boyland & Anderson, 1998; Branigan, Pickering, Stewart, & McLean, 2000; Hartsuiker & Kolk, 1998; Huttenlocher et al., 2004; Saffran & Martin, 1997) and in cross-language priming (Kootstra & Doedens, 2016).

Support for the error-driven learning mechanism as an account of the acquisition of syntax comes from a behavioural study by Peter, Chang, Pine, Blything, and Rowland (2015) on how children develop knowledge of verb argument structure, and from a priming study by Fazekas, Jessop, Pine, and Rowland (2020) which demonstrated that exposure to the same syntactic structure leads to faster learning in children if this structure was presented in a surprising context rather than a predictable context.

#### 3.1.1.2 Activation-based accounts of structural priming

An alternative to the error-driven implicit learning account explains structural priming as the result of residual activation. In the verbal model introduced by Pickering and Branigan (1998), the residual activation of syntactic representations and combinatorial nodes makes these representations and nodes easier to access and thus leads to repeated use of particular syntactic representations. In activation-based accounts priming is regarded as a short-term effect that is not cumulative and that does not last across different experimental trials.



A bilingual version of the residual activation account was proposed by Hartsuiker et al. (2004). According to this account, syntactic representations can be fully shared between languages. Findings of equally strong cross-language and within-language priming have been interpreted as strong support for this shared syntax account (Kantola & van Gompel, 2011). In other respects, the current verbal, activation-based models are unfortunately under-specified. For example, whether identical word order in prime and target sentences in different languages is necessary for priming (Bernolet, Hartsuiker, & Pickering, 2007), depends on the exact architecture of an activation-based account of structural priming. This illustrates a limitation in the usefulness of verbal models as opposed to implemented models. Verbal models allow for a high level of vagueness that is often not immediately apparent. As a consequence, fewer experimental findings can potentially contradict these theoretical accounts. In contrast, the computational implementation of a model forces the researcher to make choices regarding the specifics of the architecture that underlies a theoretical account.

Reitter, Keller, and Moore (2011) implemented a hybrid model that provides an activation-based account of structural priming but also includes learning-based long-term linguistic adaptation. In this model, the abstract hierarchical order of phrases and the surface order in which phrases appear are computed in a single step. For this reason, the model does not predict priming between sentences with different constituent orders, such as dative constructions with the prepositional object phrase placed sentence final (e.g., "*The driver showed the problem* to the mechanic.") or with the object directly after the verb ("*The driver showed* the mechanic *the problem*."). Since the model does not allow for within-language structural priming between structures with different word orders, it must also predict that such priming does not occur *between* languages, although the model has never been applied in a bilingual setting.

### 3.1.2 Cross-language structural priming

Over 20 years ago, a number of studies showed that structural priming can occur between two different languages (Hartsuiker et al., 2004; Loebell & Bock, 2003; Meijer & Fox Tree, 2003). These findings provide evidence that syntactic representations can be shared between languages, and they thus increase support for the abstract nature of those representations.



Cross-language structural priming effects have been observed in adults from a wide age range (e.g., Loebell & Bock, 2003), in adolescents (e.g., Favier, Wright, Meyer, & Huettig, 2019; Kutasi et al., 2018), and in children (e.g., Hsin, Legendre, & Omaki, 2013; Vasilyeva et al., 2010). Most of the experiments in cross-language priming include English as either the prime or target language. The only exceptions are, to the best of our knowledge, the study by Cai, Pickering, Yan, and Branigan (2011) that involved Mandarin-Cantonese bilinguals, the study by Kootstra and Şahin (2018) that involved Papiamento-Dutch bilinguals, and the study by Mercan and Simonsen (2019) that included Norwegian-Turkish bilinguals. Nevertheless, a wide variety of other languages has been studied in cross-language syntactic priming experiments, including German (e.g., Loebell & Bock, 2003), Spanish (e.g., Bock, 1986), Dutch (e.g., Desmet & Declercq, 2006), Greek (e.g., Salamoura & Williams, 2007), Korean (e.g., Shin & Christianson, 2009), Polish (Fleischer, Pickering, & McLean, 2012), Irish (Favier et al., 2019), Scottish Gaelic (Kutasi et al., 2018), and Swedish (Kantola & van Gompel, 2011). So far, only Hartsuiker et al. (2016) and Huang et al. (2019) have studied cross-language priming in trilinguals (L1 Dutch - L2s English and either French or German; and L1 Mandarin - L2s Cantonese and English, respectively).

The most common syntactic constructions under investigation in cross-language priming studies are datives (e.g., "*The woman handed the screaming baby to her husband.*" / "*The woman handed her husband the screaming baby.*") (e.g., Loebell & Bock, 2003; Meijer & Fox Tree, 2003) and transitives (e.g., "*Many people attended the concert.*" / "*The concert was attended by many people.*") (e.g., Hartsuiker et al., 2004; Loebell & Bock, 2003). Other structures that have been investigated are relative clauses (e.g., "*Someone shot the servants of the actress who was / were on the balcony.*") (e.g., Desmet

& Declercq, 2006; Kidd, Tennant, & Nitschke, 2015), genitives (e.g., "*the shirt of the boy*" / "*the boy's shirt*") (Bernolet, Hartsuiker, & Pickering, 2013), noun phrases (e.g., "*the red shark*" / "*the shark that is red*") (Bernolet et al., 2007; Hsin et al., 2013), and subject-to-object raising constructions (e.g., "*Mary believes Jerry to be trustworthy*" / "*Mary believes that Jerry is trustworthy*") (Song & Do, 2018). While most of these studies investigate structural priming in sentence production, several studies have also demonstrated such cross-language priming effects in sentence comprehension (Kidd et al., 2015; Weber & Indefrey, 2009). The majority of the work on structural priming between languages has tested priming in spoken language. Nevertheless, similar priming effects have also been demonstrated in experiments where participants produced written language (Desmet & Declercq, 2006; Favier et al., 2019; Hartsuiker et al., 2016; Kantola & van Gompel, 2011).

A considerable body of work on cross-language structural priming confirms that syntax can be shared between languages. Nonetheless, conflicting results on a number of issues remain to be fully explained. Two of these issues relate to the way in which syntactic structures are shared between languages: the relative strength of within-language and cross-language structural priming and the dependency of cross-language structural priming on identical word order between languages.

#### 3.1.2.1 Is cross-language structural priming equally strong as within-language structural priming?

Several studies have found no significant difference between the strength of within-language and cross-language structural priming (Hartsuiker et al., 2016; Kantola & van Gompel, 2011; Schoonbaert, Hartsuiker, & Pickering, 2007). In contrast, Cai et al. (2011) and Bernolet et al. (2013) have provided experimental evidence for a stronger within-language than cross-language structural priming effect. Travis, Cacoullos, and Kidd (2017) found a similar difference in a corpus study, where the within-language priming effect was not only stronger, but also longer-lived than the cross-language effect.

The quantitative difference in the experimental findings was accounted for by Bernolet et al. (2013) under the assumption that less proficient speakers of the second language (L2) have not yet developed syntactic representations that are shared across languages, or at least not for the syntactic structure under investigation. This would suggest that a prerequisite for equally strong within- and cross-language structural priming is that speakers are highly proficient in both languages.



#### 3.1.2.2 Does cross-language structural priming require structures that have identical word order?

Conflicting results have been reported on the possibility of cross-language priming between structures that have different word order. Priming was shown to occur between verb-final passives in Dutch (e.g., "*De duiker werd door de piraat opgetild.*"; literally: "The diver was by the pirate lifted.") and verb-medial passives in English (e.g., "*The boxer was chased by the nun.*") (Bernolet, Hartsuiker, & Pickering, 2009). Priming has also been demonstrated between transitives in Chinese and English (Chen, Jia, Wang, Dunlap, & Shin, 2013), between object – verb – subject order sentences in Polish and passives in English (Fleischer et al., 2012), and between datives in Korean and English (Shin & Christianson, 2009), even though syntactic structures involved in these alternations do not have identical word order between the prime and target languages. On the other hand, no such priming effects were found between transitives in German and English (Loebell & Bock, 2003), between datives in German and English (Jacob, Katsika, Family, & Allen, 2017), and between relative clauses in Dutch and English (Bernolet et al., 2007), where word order is also different between languages.

While the contrasting findings on the difference between cross-language and within-language structural priming seem to be explainable by taking into account proficiency and language dominance, no such overall explanation has been offered for the different results on the dependency of cross-language structural priming on shared word order.

### 3.1.3 The present work

In the present work, we investigate whether implicit learning can account for cross-language priming. We combine the monolingual account of structural priming with the implemented Bilingual Dual-Path model of sentence production (See Chapter 2). We train instances of the model which we then use as participants in simulated experiments. Our simulated participants differ from each other because they all have different random initial weights and their own unique language input. This language input also has a small variation in the balance between the two languages. In addition, we create differences between simulated participants by varying model parameters such as the number of units in some of the layers.

In our first simulated experiment we determine whether structural priming can occur in the model between transitives in artificially generated versions of Spanish and English. In the second experiment, we investigate whether cross-language structural priming in the model is dependent on identical word order in the syntactic structures in question. We do this by ascertaining whether priming occurs between Dutch with verb-final passives and English with verb-medial passives and comparing its strength to that of priming between Dutch and English that both have verb-medial passives. In our third simulated experiment, we explore whether the findings from the first experiment generalize to a pair of languages that are not closely related and do not include English. We implemented an Indonesian-Dutch version of the model to simulate a cross-language priming between these two languages.

We found that priming does indeed occur between all language pairs, and that priming tends to be stronger within than between languages.

## 3.2 General Method

In this section, we describe the aspects of the method that apply to all the experiments on which we report in this chapter.

**Table 3.1: Sentence types in the artificial language input for the Spanish-English model.** Example sentences are given for each sentence type in each of the two artificial languages, and the natural language sentences they represent are given underneath in parentheses.

| Sentence type | Spanish | English |
|---|---|---|
| Animate intransitive | la gata vieja está reir -ger.<br>(La gata vieja está riendo.) | the old cat is laugh -prg.<br>(The old cat is laughing.) |
| Animate with-intransitive | él ha caminar -prf con la abuela.<br>(El ha caminado con la abuela.) | he has walk -par with the grandmother.<br>(He has walked with the grandmother.) |
| Inanimate intransitive | el cacto estába caer -ger.<br>(El cacto estaba cayendo.) | the cactus was fall -prg.<br>(The cactus was falling.) |
| Locative | un camarero pequeño saltar en la bañera.<br>(Un camarero pequeño salta en la bañera.) | a small waiter jump in the bath.<br>(A small waiter jumps in the bath.) |
| Transitive (active) | el padre romper -pas la botella.<br>(El padre rompió la botella.) | the father break -pst the bottle.<br>(The father broke the bottle.) |
| Transitive (passive) | la botella es romper -prf por el padre.<br>(La botella es rota por el padre.) | the bottle is break -par by the father.<br>(The bottle is broken by the father.) |
| Cause-motion | ella está deslizar -ger el café por el pueblo<br>(Ella está deslizarando el café por el pueblo.) | she is slide -prg the coffee by the village<br>(She is sliding the coffee by the village.) |
| Benefactive transitive | la tía grande reparar un cacto para el perro<br>(La tía grande repara un cacto para el perro.) | the big aunt repair a cactus for the dog<br>(The big aunt repairs a cactus for the dog.) |
| State-change | ella llenar -pas la botella con naranja<br>(Ella llenó la botella con naranja.) | she fill -pst the bottle with orange<br>(She filled the bottle with orange.) |
| Locative alternation (LT) | el niño cepillar el lavabo con leche<br>(El niño cepilla el lavabo con leche.) | the boy brush the sink with milk<br>(The boy brushes the sink with milk.) |
| Locative alternation (TL) | el niño cepillar leche sobre un lavabo<br>(El niño cepilla leche sobre el lavabo.) | the boy brush milk on the sink<br>(The boy brushes milk on the sink.) |

3

### 3.2.1 Artificial languages



All artificially generated versions of languages that we used comprised the same nine sentence types (see examples in Table 3.1): Animate intransitive, Animate with-intransitive, Inanimate intransitive, Locative, Transitive (in active or passive form), Cause-motion, Benefactive transitive, State-change, and Locative alternation (in location-theme (LT) or theme-location (TL) form). These are the same sentence types that were used by Chang et al. (2006), with two exceptions: Chang et al. (2006) also included Transfer datives and Benefactive datives.

In the model input, sentences were paired with *messages* that consist of three parts that represent the conceptual structure of the target sentence. The first part is made up of thematic roles that are linked to concepts. The second part of the message contains event semantic information. The third part of the message contains information about the target language for the sentence.

The thematic roles used in the messages follow the so-called XYZ role encoding scheme introduced by Chang (2002). In terms of traditional thematic roles, the X role is assigned to agents, causes, and stimuli, the Y role maps to patients, themes and experiencers, and the Z role to goals, locations, recipients, and benefactors. However, the XYZ format differs from conventional thematic role assignments in that the Y role is used for both intransitive agents as well as transitive patients.

The message for Example 1 (see below), for instance, links the thematic role X to the noun concept FATHER, the thematic role ACTION-LINKING to the verb concept BREAK, and the thematic role Y to the noun concept BOTTLE. The event semantic part of the message sets the tense as PAST and the aspect as SIMPLE, and also lists the required roles for the message as X, Y, and ACTION-LINKING. Finally, the third part of the message sets the target language to Spanish. Noun concepts are accompanied by attributes that determine how the noun is realized as a noun phrase. Nouns can be expressed as pronouns, and can have a definite or indefinite article. In the example, "*a bottle*" is therefore encoded in the message as "Y = indef, BOTTLE", while "*the father*" is encoded as "X = def, FATHER". In addition, a noun phrase can contain an adjective. The noun phrase "*a big bottle*", for instance, could be encoded as "Y = indef, BOTTLE; Y-MOD =

BIG".

1. Spanish Active: el padre romper -pas una botella .
   X = def, FATHER; ACTION-LINKING = BREAK; Y = indef, BOTTLE;
   EVENT-SEM = **X:1, Y:0.5**, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = es



2. English Active: the father break -pst a bottle .
   [...];
   EVENT-SEM = **X:1, Y:0.5**, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = en

3. Spanish Passive: una botella fue romper -prf por el padre .
   [...];
   EVENT-SEM = **X:0.5, Y:1**, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = es

4. English Passive: a bottle was break -par by the father .
   [...];
   EVENT-SEM = **X:0.5, Y:1**, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = en

Messages that can be expressed using two different syntactic structures were given a strong bias towards one of those structures. This was achieved by creating differences in activation based on how each structure emphasises thematic roles in the sentence. Biasing towards an active sentence (Examples 1 and 2 above), for example, was done by giving the agent a higher activation (X:1) than the patient (Y:0.5 or Y:0.75). In the same way, a bias towards a passive sentence (Examples 3 and 4 above) was achieved with a higher activation for the patient (Y:1), than for the agent (X:0.5 or X:0.75).

In our message semantics, only singular entities, properties, and actions (that are expressed by (pro)nouns, adjectives, and verbs respectively) were used. Actions and entities were always in third person form. Because of this, our artificial languages did not have any markers for number, in contrast with the artificial English used by Chang et al. (2006), which had a plural noun marker and a singular verb marker.

### 3.2.2 Model

To simulate participants in a cross-language priming experiment, we trained the Bilingual version of the Dual-path model (Tsoukala et al., 2017)[1] to simulate simultaneous Spanish – English, Dutch – English or Indonesian – Dutch bilinguals, who start acquiring both languages from infancy.

The Bilingual Dual-path model is a modified version of the original Dual-path model (Chang, 2002; Chang et al., 2006). The model was made bilingual by exposing it to two languages and by adding a TARGET LANGUAGE layer in the meaning path that determines the intended output language. Apart from this, there are a number of minor architectural differences between the original Dual-path model and the bilingual version that we used. As is shown in Figure 2.1, the implementation used in our experiments had a REALISATION layer with separate units for realising a noun phrase with a pronoun, a definite article, or an indefinite article. The original Dual-path model, in contrast, had a single unit with different levels of activation for each of the three possible realisations of a noun phrase (Chang et al., 2006). The two implementations of the model also differ slightly in the activation functions that are used. The original model used the tanh activation function (a non-linear function with an output range between $-1$ and 1) for all layers, except for the OUTPUT and COMPREHENDED ROLE layers, which used softmax (a non-linear function with an output range between 0 and 1, and a sum that equals 1). The implementation by Tsoukala et al. (2017), however, also used softmax activation for the predicted ROLE layer. This helped the model to overcome a difficulty it had with learning the correct gender and definiteness for articles (e.g., "*a*" vs. "*the*"). Finally, unlike the original Dual-path model, our implementation did not have a layer that enhances the model's memory for the roles it has produced by keeping a running average of those activations.

Following Tsoukala, Broersma, et al. (2021), we increased the generalizability of our results by introducing small variations in the configuration of the models. Our models had a number of hidden layer units that was sampled from a uniform distribution

[1]The Bilingual Dual-path model can be downloaded from: `https://github.com/xtsoukala/dual_path`. It includes the code to run a cross-language priming experiment.

between 58 and 62, and a number of compress layer units sampled from a uniform distribution between 38 and 42. The fixed weight value for concept–role connections was sampled from a uniform distribution between 13 and 17. The sentences were approximately equally divided over the two languages, where the language percentage of English was sampled from a uniform distribution between 48 to 52% and the rest was Spanish. Other than this, we used the model's default settings.



### 3.2.3 Training and testing input

For each simulated participant, a set of 8,000 unique message-sentence pairs was randomly generated and different random initial connection weights were used. 80% of these sentences were used for training, while 20% were set aside for testing the accuracy of the model. This means that there was no overlap between the training and test sets. This contrasts with accuracy testing in Chang et al. (2006), where the same test set was used for all trained models, and there was a small overlap (less than 1%) between training and test. We did follow Chang et al. (2006) in excluding the message from 25% of training pairs. This increases the syntactic nature of the representations that the model learns (Chang et al., 2015). The models iterated over their training sets 16 times. After each of these 16 epochs, model accuracy was tested using the test set. The order of the training set was randomised at the beginning of each epoch. We modelled balanced bilingual speakers by training the model on both languages from the beginning and on approximately equal numbers of sentences in each language.

Because our aim was to verify the possibility of structural priming between different languages, we designed the training input to maximise the likelihood of revealing an effect. If a structure is produced very frequently irrespective of priming, ceiling effects might cause the priming effect to become smaller and therefore harder to detect. We addressed this issue by using balanced frequencies of the structures under investigation. This means that, unlike in natural language, actives and passives occurred with the same frequency in the training input we provided the model.

### 3.2.4 Priming Experiment

Independent of the training and test sets, a single set of experimental trials was generated that was used to perform the priming experiment on all of the simulated participants. Each trial consisted of a combination of a unique prime sentence and a unique target message that did not have any semantic overlap in terms of their verb, agent, and patient. Whereas the messages in the training data had activations of 0.5 or 0.75 for the de-emphasized role, we gave the target messages in the priming experiment only the weaker bias, by always giving the de-emphasised roles an activation of 0.75. In this way, we follow Chang et al. (2006) in simulating that stimuli in structural priming experiments generally do not have a strong bias towards one syntactic structure over another.

With two Language Combination conditions (Cross-language and Within-language) and two Prime Language conditions, we had four possible combinations of prime and target language, for example: English – English, Spanish – Spanish, Spanish – English, and English – Spanish. We had equal numbers of each of these four language combinations, which in turn means that there were equal numbers of within- and cross-language trials. We also had equal numbers of trials with active and passive primes, and equal numbers of trials with active- and passive-bias target messages. The two levels for Prime Structure, Language Combination, Prime Language, and Target-message Bias combine for a total of 16 different conditions. We had 50 prime-target combinations that all occurred as each of the 16 different conditions. This means that each experiment consisted of 800 trials.

The priming experiment was performed on the models after 16 training epochs. As was done in Chang et al. (2006) and Chang et al. (2015), we presented the models with prime sentences without a message, and with learning turned on in the model. After each prime, a response was elicited from the model by presenting it with a target message.

We used a learning rate of 0.2 during the priming experiment, which was slightly higher than the learning rate of 0.15 used by Chang et al. (2006), but considerably lower than the learning rate of 0.6 used by Chang et al. (2015). According to Chang et al. (2015), prediction error in an artificial language is smaller than in natural language because of its smaller size and complexity. This reduced prediction error can lead to smaller priming effects. Because our artificial languages have fewer syntactic structures than those of Chang et al. (2006), but many more structures than Chang et al. (2015), we used a learning rate that was closer to Chang et al. (2006).



After each trial, the connection weights were reset to the values they had before starting the priming experiment. The state in which the model encountered each trial was thus the same for all of the trials. Hence, there was no between-trial priming or any other learning effects during the experiment. This means that the order of the trials did not need to be (pseudo-)randomised across simulated participants.

## 3.3 Spanish – English (Experiment 1)

### 3.3.1 Research Questions

We perform a computational modelling experiment to further test the viability of error-driven implicit learning as an account of structural priming in general and of cross-language structural priming specifically. We simulate cross- and within-language priming of actives and passives, using artificial versions of Spanish and English. Furthermore, we investigate if cross-language priming differs quantitatively from within-language priming in the model.

We expect cross-language structural priming to occur, because it has been demonstrated in adults by Hartsuiker et al. (2004), and in children by Vasilyeva et al. (2010), for the languages and the syntactic structures used in the present experiment. Additionally, as mentioned above, Chang et al. (2006) have shown that within-language priming of English transitives (and other syntactic structures) occurs in the model. The analyses in that study revealed that the model builds syntactic representations that largely abstract away from lexical items. The model does this in a way that is mostly consistent with results from behavioural studies. We expect that the model's syntactic representations will similarly abstract away from the target language and will therefore enable cross-language structural priming in the model in line with findings from behavioural studies. Finally, a bilingual version of the Dual-path model has demonstrated the ability to code-switch (Tsoukala, Broersma, et al., 2021), and code-switching has been interpreted as an indication that syntax is shared between languages (Kootstra, Van Hell, & Dijkstra, 2010; Loebell & Bock, 2003). This notion of shared syntactic representations is also what should make cross-language structural priming possible (Hartsuiker et al., 2004).

Assuming the model does display cross-language structural priming, we have no strong expectation of whether or not it will differ in strength from within-language priming, for two reasons. Firstly, as mentioned in the Introduction, an error-driven implicit learning account does not make any prediction about a difference in the strength of cross-language versus within-language priming. Secondly, as was also described in the Introduction, some behavioural experiments reveal that within-language priming is significantly stronger than cross-language priming, while others do not find a significant difference between the two types of priming. While we do not have a clear expectation, we aim to meet the proficiency prerequisite for equivalent within- and cross-language priming effects that was suggested by Bernolet et al. (2013) by simulating balanced bilingual speakers, who are equally proficient in both languages. If our results do reveal a difference, we expect within-language priming to be stronger than cross-language priming.

### 3.3.2 Method

#### 3.3.2.1 Artificial languages

Table 3.1 gives examples of each of the sentence types that were used in Experiment 1[2].

The two languages together have 258 unique lexical items. In addition to nouns, verbs, adjectives, determiners, and prepositions, these lexical items include inflectional morphemes such as a past tense marker (Spanish: "*-pas*"; English: "*-pst*") and a past participle marker (Spanish: "*-prf*"; English: "*-par*"). Spanish has 135 items while English has 126. These include one item that occurred in both languages: the period

[2]The files that the model requires to generate the artificial language input, and the input for the priming experiment can be found here: `https://github.com/khoe-yh/cross-lang-struct-priming`

".". Each of the two languages has 44 nouns, 4 pronouns, 51 verbs, 12 prepositions, and 3 inflectional morphemes. English had 2 determiners, 6 adjectives, and 3 auxiliary verbs, while Spanish had 4 determiners[3], 11 adjectives, and 5 auxiliary verbs.

#### 3.3.2.2 Simulated participants



There was considerable variability in how successfully the simulated participants learned the artificial languages. We therefore trained 120 models and selected the 80 simulated participants with the highest meaning accuracy (i.e., percentage of grammatically correct sentences that convey the target message without any additions, over all test sentences). The accuracy scores for these simulated participants varied from 71.85% to 93%, with a mean of 77.54%. The percentage of grammatically correct sentences for these simulated participants varied from 96.70% to 99.95%, with a mean of 99.40%. Supplementary analyses of the experiments in this chapter include all 120 simulated participants (see Appendix 3.A of this chapter). The supplementary analyses reveal the same patterns of results as the analyses in the current chapter.

### 3.3.3 Results

Our analysis only included those responses that correctly conveyed the target message, either with an active or a passive structure. However, we disregarded errors involving definiteness of articles or missing periods. We included 71.75% of the responses on cross-language trials and 65.67% of responses on within-language trials.

#### 3.3.3.1 Descriptive statistics

On cross-language trials, 51.93% of sentences that simulated participants produced were passives after a passive prime, while 49.50% of sentences were passives after an active prime. On within-language trials, 53.48% of the produced sentences were passives after a passive prime, whereas 48.25% of sentences were passives after an active prime. Figure 3.1 visualises the priming effect, in that there were more passive

[3] For Spanish, the lexical item "*la*" is both a determiner and a pronoun.

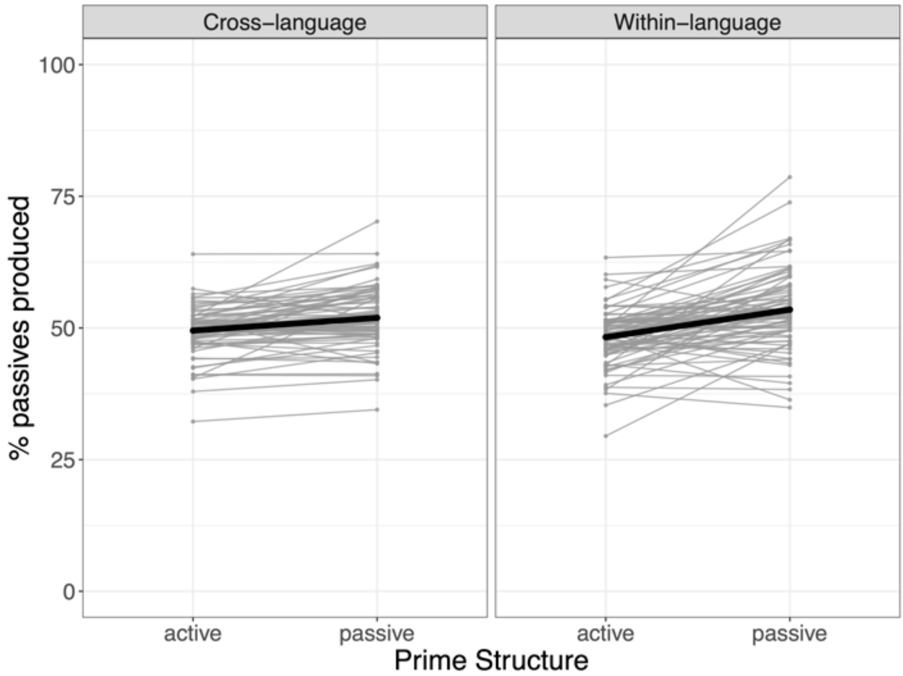



**Figure 3.1:** Percentage of responses in Experiment 1 (Spanish-English) that had a passive structure after either an active prime or a passive prime, for cross-language trials (on the left) or within-language trials (on the right). The thick black lines visualise the priming effect across all analysed trials by connecting the percentage of passives responses after active primes to the percentage of passive responses after passive primes. The thin grey lines show the same for each individual simulated participant.

responses after passive primes than after active primes, for both Language Combination conditions. The plot also shows that the effect was similar for cross-language and within-language priming, with a somewhat stronger effect for within-language trials.

#### 3.3.3.2 Pre-registered analysis

As pre-registered[4], we analysed[5] the data from our experiment with a Bayesian logistic mixed-effects model, with a logit link function, using the function brm from the package brms (version 2.12.0; Bürkner, 2017, 2018) in R (version 3.5.1; R Core Team, 2018a). The model predicts a binary dependent variable, Is Passive, that indicates whether the sentence structure that the model produced was passive (1), or active (0). The predictors of interest were Language Combination (Cross-language = 0, Within-language = 1), Prime Structure (Active = −0.5, Passive = 0.5), and their interaction. In addition, the model includes two other contrast-coded predictors: Target-message Bias (Active = −0.5, Passive = 0.5) and Prime Language (English = −0.5, Spanish = 0.5). Because our main interest is in cross-language priming, Language Combination was dummy-coded with Cross-language as the reference level. The inclusion of the interaction between Language Combination and Prime Structure means that we can then interpret the estimate of the Prime Structure predictor at that reference level of Language Combination. The other predictors were contrast-coded since they lacked a meaningful reference level in the context of our research questions. We fit random intercepts for items and simulated participants, as well as by-participant random slopes for Language Combination, Prime Structure, and their interaction[6]. We did not include correlations between random effects.

Regularizing priors were used in all our models, which give a minimal amount of information with the objective of yielding stable inferences. Prior means were 0, and did thus not bias towards specific effects. The only exception to this was the Target-message Bias predictor for which we used a prior with a Gamma distribution to ex-

[4]The pre-registration can be accessed here: `https://aspredicted.org/blind.php?x=bu632c`

[5]Our analysis scripts can be found here: `https://github.com/khoe-yh/cross-lang-struct-priming`

[6]We did not fit by-item random slopes, because an earlier version of our analysis, that did include them, did not result in valid and reliable parameter estimates. This was apparent from the large number of divergent transitions after warmup, and the low Bulk and Tail Effective Sample Sizes (ESS) (`https://mc-stan.org/misc/warnings.html`). Analysis of the output of the earlier regression model revealed that the ESS values were specifically related to the estimates of the by-item random slopes for Language Combination. In addition, the credible interval (CrI) for these estimates were consistently close to zero across different numbers of iterations and chains, and different values for the adapt_delta parameter.

Table 3.2: **Summary of the fixed effects in the Bayesian logistic mixed-effects model ($N = 45,310$)** for Experiment 1. For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive (*P*(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE).



| Predictor | Est. | 95% CrI | *P*(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | 0.29 | [−0.03, 0.61] | 0.97 |
| LANGUAGE COMBINATION | 0.13 | [−0.07, 0.33] | 0.90 |
| PRIME STRUCTURE | 0.82 | [0.51, 1.13] | 1.00 |
| PRIME LANGUAGE | 0.28 | [0.16, 0.41] | 1.00 |
| TARGET-MESSAGE BIAS | 9.36 | [9.14, 9.59] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.90 | [0.57, 1.22] | 1.00 |

clude negative values. The standard deviations for the priors that we used for the predictors are based on the effect sizes that resulted from an earlier version of the experiment.

The regression analysis results are summarised in Table 3.2. The positive estimate for the PRIME STRUCTURE predictor (Estimate of the log-odds ratio = 0.82, 95% CrI = [0.51, 1.13]) indicates that more passives were produced when the PRIME STRUCTURE was passive than when it was active. The estimate has a credible interval far from zero. This means that there was a clear priming effect at the reference level (i.e., cross-language) of the LANGUAGE COMBINATION predictor. We interpret this as strong evidence for cross-language priming in the Dual-path model. The top panel of Figure 3.2 shows the posterior distribution of the estimate for the PRIME STRUCTURE predictor.

The estimate for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE (Estimate of the ratio of log-odds ratios = 0.90, 95% CrI = [0.57, 1.22]) with a credible interval that only includes positive values, provides strong evidence for a difference between within-language and cross-language priming. This is visualised in the bottom panel of Figure 3.2, which shows the posterior distribution of the interaction. The positive value of the estimate indicates that the priming effect was stronger for within-language than for cross-language trials, since the log-odds ratio that compares production of passives after passive or active primes on within-language trails was larger than the log-odds ratio that compares the production of passives after passive or active primes on cross-language trials.

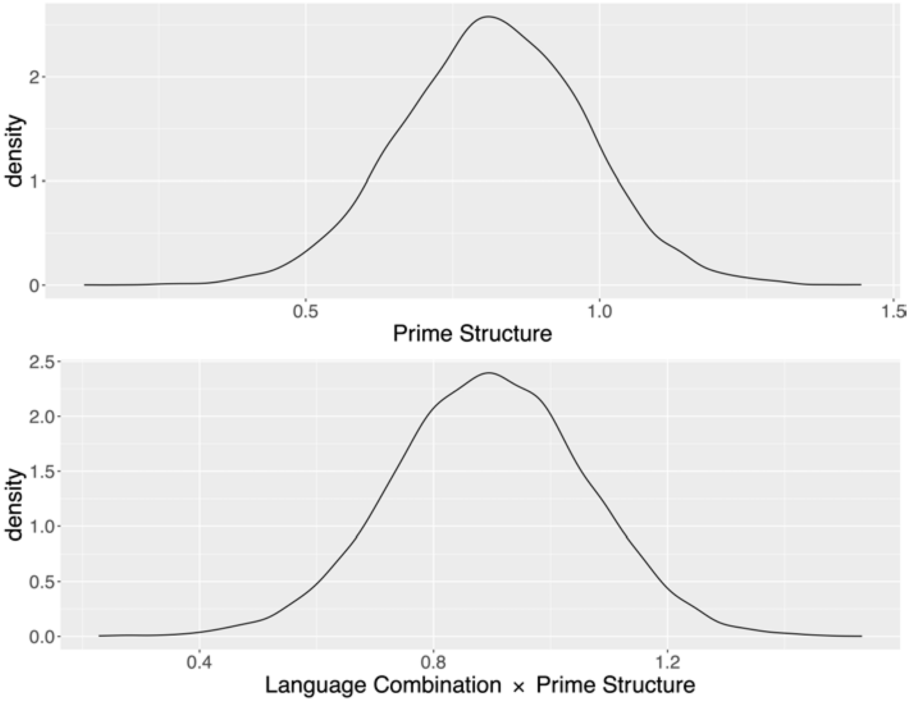



**Figure 3.2:** Posterior distributions of the estimate for the PRIME STRUCTURE predictor (top) and of the estimate for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE (bottom) in Experiment 1 (Spanish-English).

### 3.3.4 Discussion

The results of Experiment 1 reveal a clear and strong cross-language structural priming effect. We thus provide evidence for the viability of implicit learning as an account of cross-language structural priming. In turn, our finding provides support for the implicit learning model implemented in Dual-path, as an account of structural priming in general. We should note, however, that this finding does not provide evidence against other implemented models of structural priming. The hybrid model introduced by Reitter et al. (2011), for example, also predicts cross-language structural priming to occur. Fortunately, a way to empirically distinguish between this hybrid account and the Dual-path account is available. As explained in Section 3.1.1.2, the hybrid account predicts that priming will not occur between structures in different languages that do not have the same word order (Reitter et al., 2011). The Dual-path account, on the other hand, does not rule out such a priming effect. In our next experiment, we investigate if structural priming in our model requires identical word order by testing whether priming can occur between Dutch verb-final passives and English verb-medial passives.

## 3.4 Verb-final Dutch – English (Experiment 2a) and verb-medial Dutch – English (Experiment 2b).

### 3.4.1 Introduction

In Experiment 1 we demonstrated that priming of transitives occurs between Spanish and English. Both actives and passives have the same word order between these languages. This is not the case for the combination of Dutch and English. While actives always have identical word order across these two languages, passives do not, because Dutch has more flexible word order than English. In passive sentences, the participle verb can be placed either before (1) or after (2) the agent noun. While priming between these Dutch passives and passives in English has been demonstrated experimentally, it remains controversial how structural priming depends overall on surface word order.

1. De kerk wordt getroffen door de bliksem. (The church is struck by lightning)

2. De kerk wordt door de bliksem getroffen. (The church is by lightning struck)

#### 3.4.1.1 Evidence for cross-language structural priming between sentences with different word order

Several studies have provided evidence for priming between different languages for syntactic structures without identical word order. Bernolet et al. (2009) have shown that priming occurs between Dutch and English, not only for those passive constructions that are the same between the two languages (1), but also for those that differ in terms of word order (2). Their study, however, did reveal the former effect to be stronger than the latter. According to the authors, this indicates that priming is a phenomenon that not only occurs at the level of syntactic structure, but also at the level of information structure.

Further evidence for structural priming of transitives without identical word order comes from Chen et al. (2013), who demonstrated that priming occurs between verb-final passives in Chinese (e.g., "杯子被小猫打破了" ("*the cup* **bei**[7] *the cat break-perfective*")) and verb-medial passives in English (e.g., "*The cup was broken by the cat.*"). Similar priming effects for a different syntactic construction have been presented by Shin and Christianson (2009). Their results revealed priming of datives with prepositional phrase – noun phrase – verb (PP-NP-V) order in Korean, and datives with noun phrase – prepositional phrase – verb (NP-PP-V) order in English. Finally, priming of English passives was found by Fleischer et al. (2012) from Polish object–verb–subject order sentences (e.g., "*Kowboja budzi baletnica.*" ("*The cowboy* [object] *wake the ballet dancer* [subject]."')).

#### 3.4.1.2 Evidence against cross-language structural priming between sentences with different word order

Contrasting findings can also be found in the literature. The earliest cross-language priming study to include prime-target pairs that had different word order was performed by Loebell and Bock (2003). They investigated priming between German and English for datives and transitives. Their results show priming effects between

[7] **bei** is a passive marker in Chinese

the two languages for datives, which have identical word order. However, no such effect was found for transitives, which are verb-final for German but verb-medial for English (e.g., German: "*Die Böden werden täglich von dem Hausmeister gereinigt.*"; English: "*The floors are cleaned daily by the janitor.*"). There was a non-significantly increased production of active targets after active primes. Surprisingly, there was a (non-significant) decrease in the production of passive sentences after passive primes.

3

Additionally, Jacob et al. (2017) did not find evidence for cross language priming of datives between verb-final subordinate clauses in German and verb-medial subordinate clauses in English (e.g., German: "*Kristin dachte, dass der Rechtsanwalt den Vertrag an den Klienten schickte.*"; English: "*Kristin thought that the lawyer sent the contract to the client.*").

Bernolet et al. (2007) also did not find priming of relative clauses between Dutch and English (e.g., Dutch: "*de pan die blauw is*"; English: "*the pan that is blue*"), which don't share relative clause word order, while they did find a priming effect for these relative clauses between Dutch and German (e.g., Dutch: "*de haai die rood is*"; German: "*der Hai der rot ist*"), which do share relative clause word order.

#### 3.4.1.3 Interpretation of the available experimental evidence

We interpret the findings of priming between structures with different word order in different languages as convincing evidence for the existence of such an effect. The reports of the absence of these types of effects in other studies provide comparatively weaker evidence to the contrary, since the absence of a significant effect is not proof that an effect does not exist (Vasishth & Nicenboim, 2016). Based on the available behavioural results, we therefore conclude that cross-language structural priming can occur in multilingual speakers for structures that do not have identical word order. Nonetheless, the conflicting findings remain to be fully explained. It is therefore unclear under which circumstances cross-language priming for structures with different word order does or does not occur.

### 3.4.2 Research Questions

We perform a pair of experiments to answer the question to what extent cross-language priming in an error-driven implicit learning account of structural priming depends on identical word order between languages. We answer this question by determining if cross-language priming can occur between Dutch and English passives in the bilingual Dual-path model. In the first of the two experiments, Experiment 2a, we use a version of Dutch that has verb-final passives, which have a different word order than English passives. In the second experiment, Experiment 2b, we use a version of Dutch that has verb-medial passives, which have the same word order as English passives. These experiments will also answer the question whether the results of Experiment 1 generalise to a different language pair. Furthermore, if a priming effect between English and both versions of Dutch is found, our results will give some indication of whether the strength of the priming effect decreases when word order similarity decreases.

According to Reitter et al. (2011), the hybrid account of structural priming that they implemented predicts that cross-language priming is only possible when linear word order is shared between structures. On the other hand, it is not clear what an error-driven implicit learning account predicts for structures that don't share word order. However, in performing our experiment we can establish a prediction on this issue. If our model, as an implementation of the error-driven learning account of structural priming, displays priming between structures with different word order, this would imply that the error-driven learning account (unlike the hybrid account) predicts such priming. In this way, our results might contribute to distinguishing between the two implemented accounts of structural priming.

### 3.4.3 Method

#### 3.4.3.1 Artificial languages

The version of English that we used for Experiments 2a and 2b was the same as for Experiment 1. The artificial versions of Dutch only differ from each other in that all passive

Transitive and passive Theme-experiencer sentences, as well as sentences that have progressive or perfect aspect, are verb-final in Experiment 2a (e.g., "*de fles wordt door de vader breken -vdw* ." ("*The bottle is by the father broken.*")) and verb-medial in Experiment 2b (e.g., "*de fles wordt breken -vdw door de vader* ." ("*The bottle is broken by the father.*")). [8].



One of the main differences between Dutch and the languages of Experiment 1 is its gender system. We implement the Dutch syntactic gender system as having two values: common (definite article: "*de*") or neuter (definite article: "*het*"). In contrast with Spanish, syntactic gender in this system does not largely agree with semantic gender. Animate nouns, for example, almost always have common gender, independent of whether they are semantically male (e.g., "*de man*" ("*the man*")) or female (e.g., "*de vrouw*" ("*the woman*")), with only a few exceptions that have neuter gender (e.g., "*het meisje*" ("*the girl*")). It is likely that this makes the Dutch gender system harder to learn for the model than the Spanish gender system. In Spanish, there are three consistent sources of information on the gender of an animate noun. The first two sources are the agreement with determiners and with adjectives based on the syntactic gender of these nouns. The third source is the semantic gender that determines by which pronoun an animate noun is expressed. These sources of information never conflict in the version of Spanish we use. The animate nouns "*niña*" ("*girl*") and "*señora*" ("*lady*"), for example should both be accompanied by the female form of determiners and adjectives and are also both expressed by the pronoun "*ella*" ("*she*"). In Dutch on the other hand, there are only two sources of information that, in addition, do not always coincide. For example, the animate nouns "*meisje*" ("*girl*") and "*vrouw*" ("*woman*") should be expressed by the same pronoun "*zij*" ("*she*"), because they have the same semantic gender, but they should be accompanied by different determiners, since they have different syntactic gender.

Table 3.3 gives an overview of all the sentence types that occur in the artificial languages we use in the Dutch-English experiments. We included all the sentence types

[8] The files that the models require to generate the artificial language input, and the input for the priming experiments can be downloaded from GitHub: `https://github.com/khoe-yh/cross-lang-struct-priming`

Table 3.3: **Sentence types in the languages for the Dutch-English models.** Examples for sentence types in the two artificial languages, with natural language sentences they represent in parentheses.

| Sentence type | Dutch | English |
|---|---|---|
| Animate with-intransitive | hij heeft wandelen -vdw met de oma. | he has walk -par with the grandmother. |
| | (Hij heeft gewandeld met de oma.) | (He has walked with the grandmother.) |
| Animate intransitive | de oude kat is lachen -dur. | the old cat is laugh -prg. |
| | (De oude kat is aan het lachen.) | (The old cat is laughing.) |
| Inanimate intransitive | de cactus was vallen -dur. | the cactus was fall -prg. |
| | (De cactus was aan het vallen.) | (The cactus was falling.) |
| Locative | een kelner springen in het bad. | a waiter jump in the bath. |
| | (Een kelner springt in het bad.) | (A waiter jumps in the bath.) |
| Transitive (active) | de vader breken -ver de fles. | the father break -pst the bottle. |
| | (De vader brak de fles.) | (The father broke the bottle.) |
| Transitive (verb-final Dutch passive) | de fles wordt door de vader breken -vdw. | |
| | (De fles wordt gebroken door de vader.) | the bottle is break -par by the father. |
| Transitive (verb-medial Dutch passive) | de fles wordt breken -vdw door de vader. | (The bottle is broken by the father.) |
| | (De fles wordt gebroken door de vader.) | |
| Theme-experiencer (active) | de nieuwe tante verbazen een gastvrouw | the new aunt surprise a hostess |
| | (De nieuwe tante verbaast een gastvrouw.) | (The new aunt surprises a hostess.) |
| Theme-experiencer verb-medial Dutch passive | een gastvrouw wordt verbazen -vdw door de nieuwe tante | |
| | (Een gastvrouw wordt verbaasd door de nieuwe tante.) | a hostess is surprise -par by the new aunt |
| Theme-experiencer (verb-final Dutch passive) | een gastvrouw wordt door de nieuwe tante verbazen -vdw | (A hostess is surprised by the new aunt.) |
| | (Een gastvrouw wordt door de nieuwe tante verbaasd.) | |
| Cause-motion | zij schuiven de koffie rondom een dorp. | she slide the coffee around a village. |
| | (Zij schuift de koffie rondom een dorp.) | ((She slides the coffee around a village.)) |
| Benefactive transitive | de grote tante repareren een cactus voor de hond. | the big aunt repair a cactus for the dog. |
| | (De grote tante repareert een cactus voor de hond.) | (The big aunt repairs a cactus for the dog.) |
| State-change | zij vullen -ver de fles met sinaasappel. | she fill -pst the bottle with orange. |
| | (Zij vulde de fles met sinaasappel.) | (She filled the bottle with orange.) |
| Locative alternation (LT) | de jongen borstelen een wastafel met melk. | the boy brush a sink with milk. |
| | (De jongen borstelt een wastafel met melk.) | (The boy brushes a sink with milk.) |
| Locative alternation (TL) | de jongen borstelen melk op een wastafel. | the boy brush milk on the sink. |
| | (De jongen borstelt melk op een wastafel.) | (The boy brushes milk on the sink.) |

that were used in Experiment 1. The lexicon of the two languages together consisted of 254 unique lexical items. Dutch had 129 items while English had 126. These include the period (".") that occurred in both languages. Each language had 44 nouns, 51 verbs, 4 pronouns, 12 prepositions, 6 adjectives, and 3 inflectional morphemes. English had 2 determiners and 3 auxiliary verbs, while Dutch had 3 determiners and 4 auxiliary verbs.



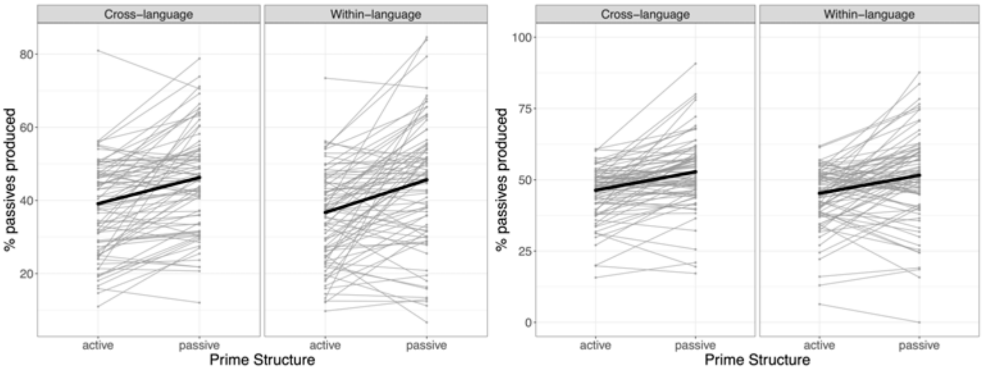
#### 3.4.3.2 Simulated participants

As was the case for Experiment 1, there was considerable variability in how successfully the simulated participants learned the artificial languages. Therefore, we again selected the 80 simulated participants with the highest meaning accuracy out of the 120 models that we trained. The accuracy scores for the models in Experiment 2a varied from 61.10% to 92.45%, with a mean of 74.69%, while for the models in Experiment 2b they varied from 79.70% to 99.15%, with a mean of 88.61%. The percentage of grammatically correct sentences varied from 88.80% to 100%, with a mean of 98.22% for Experiment 2a, and varied from 95.30% to 100%, with a mean of 99.06% for Experiment 2b.

### 3.4.4 Results

#### 3.4.4.1 Descriptive statistics

The same exclusion criteria that were used for Experiment 1, were applied to the data from Experiments 2a and 2b. That is, responses that did not correctly convey the target message were excluded from the analysis. Only errors involving definiteness of articles and missing periods were ignored. Based on these exclusion rules, we analysed 65.43%, of responses on cross-language trials and 56.42% of responses on within-language trials from Experiment 2a and 79.61%, of responses on cross-language trials and 70.80% of responses on within-language trials from Experiment 2b. For cross-language trials in Experiment 2a, 46.27% of sentences that simulated participants produced were passives after a passive prime, while 39.12% of sentences were passives after an active prime. On within-language trials in this experiment, 45.63% of the pro-




*(a) Exp 2a: verb-final Dutch-English* *(b) Exp 2b: verb-medial Dutch-English*

**Figure 3.3:** Percentage of responses in Experiment 2a (verb-final Dutch-English, left panel) and Experiment 2b (verb-medial Dutch-English, right panel) that had a passive structure after either an active or a passive prime, split by within- or cross-language trials. The thick black lines visualises the priming effect across all analysed trials by connecting the percentage of passives responses after active primes to the percentage of passive responses after passive primes. The thin grey lines show the same for each individual simulated participant.

duced sentences were passives after a passive prime, whereas 36.7% of sentences were passives after an active prime. For cross-language trials in Experiment 2b, 52.80% of sentences that simulated participants produced were passives after a passive prime, while 46.34% of sentences were passives after an active prime. On within-language trials in this experiment, 51.58% of the produced sentences were passives after a passive prime, whereas 45.27% of sentences were passives after an active prime. Figure 3.3 visualises the overall priming effects in each experiment for both LANGUAGE COMBINATION conditions, and it shows that the effects were similar across conditions but slightly larger for within-language trials than for cross-language trials.

Table 3.4: **Summary of the fixed effects in the Bayesian logistic mixed-effects model ($N = 42,462$) for Experiment 2a (verb-final Dutch-English).** For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive (*P*(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE).



| Predictor | Est. | 95% CrI | *P*(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | −0.04 | [−0.37, 0.27] | 0.39 |
| PRIME STRUCTURE | 1.34 | [0.96, 1.74] | 1.00 |
| LANGUAGE COMBINATION | 0.05 | [−0.12, 0.22] | 0.71 |
| PRIME LANGUAGE | 0.26 | [0.15, 0.36] | 1.00 |
| TARGET-MESSAGE BIAS | 7.94 | [7.76, 8.13] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.87 | [0.60, 1.13] | 1.00 |

#### 3.4.4.2 Pre-registered analyses

We performed pre-regisered analyses[9] for Experiment 2a and 2b that were based on the analysis that we performed for Experiment 1. Additionally, we analysed the cross-language trials from both experiments together. The results of the regression analyses are summarised in Table 3.4 for Experiment 2a, in Table 3.5 for Experiment 2b, and in Table 3.6 for the combined analysis of cross-language trials from both experiments.

EXPERIMENT 2A For Experiment 2a (verb-final Dutch-English), the positive estimate for the PRIME STRUCTURE predictor (Estimate of the log-odds ratio = 1.34, 95% CrI = [0.96, 1.74]) reveals that more passives were produced when the PRIME STRUCTURE was passive than when it was active. The estimate has a credible interval far from zero. This indicates a clear priming effect at the reference level (i.e., cross-language) of the LANGUAGE COMBINATION predictor. We interpret this as clear evidence for cross-language priming in the Dual-path model for structures with different word order. The estimate for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE (Estimate of the ratio of log-odds ratios = 0.87, 95% CrI = [0.60, 1.13]) with a credible

[9] The pre-registration for Experiments 2a and 2b can be accessed here: `https://aspredicted.org/blind.php?x=xq75r3` and the pre-registration for the combined analysis can be accessed here: `https://aspredicted.org/blind.php?x=m7cx3h`

Table 3.5: **Summary of the fixed effects in the Bayesian logistic mixed-effects model ($N = 52,176$) for Experiment 2b (verb-medial Dutch-English).** For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive (*P*(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE).



| Predictor | Est. | 95% CrI | *P*(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | 0.33 | [0.01, 0.64] | 0.98 |
| PRIME STRUCTURE | 1.13 | [0.81, 1.45] | 1.00 |
| LANGUAGE COMBINATION | −0.02 | [−0.15, 0.11] | 0.39 |
| PRIME LANGUAGE | 0.60 | [0.52, 0.69] | 1.00 |
| TARGET-MESSAGE BIAS | 7.29 | [7.15, 7.43] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.38 | [0.14, 0.61] | 1.00 |

interval that only includes positive values, indicates that within-language priming was stronger than cross-language priming. The solid lines in Figure 3.4 visualise the priming effect (top panel) and the interaction (bottom panel). The positive value of the estimate indicates that the priming effect was stronger for within-language than for cross-language trials, since the log-odds ratio that compares production of passives after passive or active primes on within-language trails was larger than the log-odds ratio that compares the production of passives after passive or active primes on cross-language trials.

EXPERIMENT 2B For Experiment 2b (verb-medial Dutch-English), the positive estimate for the PRIME STRUCTURE predictor (Estimate of the log-odds ratio = 1.13, 95% CrI = [0.81, 1.45]) also reveals that more passives were produced when the PRIME STRUCTURE was passive than when it was active. The estimate has a credible interval far from zero. This indicates a clear priming effect at the reference level (i.e., cross-language) of the LANGUAGE COMBINATION predictor. As was the case for Experiment 2a, the estimate for the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE (Estimate of the ratio of log-odds ratios = 0.38, 95% CrI = [0.14, 0.61]) with a credible interval that only includes positive values, indicates that within-language priming was stronger than cross-language priming. The dashed lines in Figure 3.4 visualise the priming effect (top panel) and the interaction (bottom panel). The positive value of the estimate indicates that the priming effect was stronger for within-language than for cross-language trials, since the log-odds ratio that compares production of passives after passive or active primes on within-language trails was larger than the log-odds ratio that compares the production of passives after passive or active primes on cross-language trials.

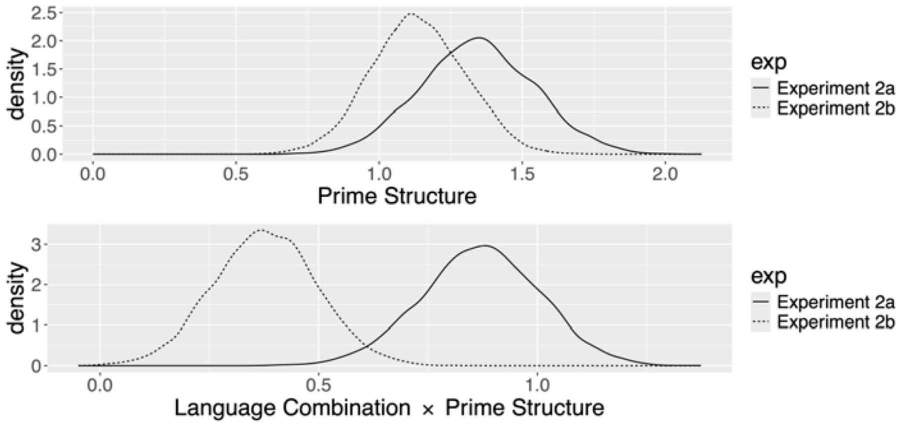



**Figure 3.4:** Posterior distributions of the estimates for the PRIME STRUCTURE predictors (top) and of the interaction between LANGUAGE COMBINATION and PRIME STRUCTURE (bottom) for Experiment 2a (verb-final Dutch-English, solid line) and Experiment 2b (verb-medial Dutch-English, dashed line).

COMBINED ANALYSIS OF CROSS-LANGUAGE TRIALS This combined analysis differs from the analyses for Experiments 1, 2a and 2b in only three respects. Firstly, the analysis has no LANGUAGE COMBINATION predictor (and therefore no interaction between that predictor and PRIME STRUCTURE) because it only includes cross-language trials. Secondly, it includes a DUTCH PASSIVE STRUCTURE (Verb-final = −0.5, Verb-medial = 0.5) predictor, and its interaction with PRIME STRUCTURE. Thirdly, there are by-item random slopes for PRIME STRUCTURE, but not for the interaction between PRIME STRUCTURE and DUTCH PASSIVE STRUCTURE, since simulated participants learned and produced only one of the two passive structures.

**Table 3.6: Summary of the fixed effects in the Bayesian logistic mixed-effects model ($N = 52,176$) for the combined analysis of the cross-language trials from Experiment 2a and 2b (verb-final and verb-medial Dutch-English).** For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive ($P$(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, DUTCH PASSIVE STRUCTURE, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between DUTCH PASSIVE STRUCTURE and PRIME STRUCTURE).

| Predictor | Est. | 95% CrI | $P$(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | −4.59 | [−4.87, −4.31] | 0.00 |
| PRIME STRUCTURE | 1.13 | [0.87, 1.39] | 1.00 |
| DUTCH PASSIVE STRUCTURE | 0.38 | [0.22, 0.53] | 1.00 |
| PRIME LANGUAGE | 0.46 | [0.37, 0.55] | 1.00 |
| TARGET-MESSAGE BIAS | 7.36 | [7.23, 7.50] | 1.00 |
| DUTCH PASSIVE STRUCTURE × PRIME STRUCTURE | 0.13 | [−0.07, 0.34] | 0.90 |

For the analysis of all the cross-language trials from both Experiments 2a and 2b, the 95% credible interval for the estimate of the interaction between DUTCH PASSIVE STRUCTURE and PRIME STRUCTURE included positive as well as negative values (Estimate of the ratio of log-odds ratios = 0.13, 95% CrI = [−0.07, 0.34]). Although the positive value of the estimate suggests that the cross-language priming effect might be weaker when passives had a different word order (Experiment 2a with verb-final Dutch passives) than when word order was the same (Experiment 2b with verb-medial Dutch passives), the statistical analysis does not provide sufficient confidence that this is indeed the case. The posterior probability of the interaction being positive given the data, $P(\text{Est.} > 0) = 0.90$ confirms this, which is visualised in Figure 3.5.

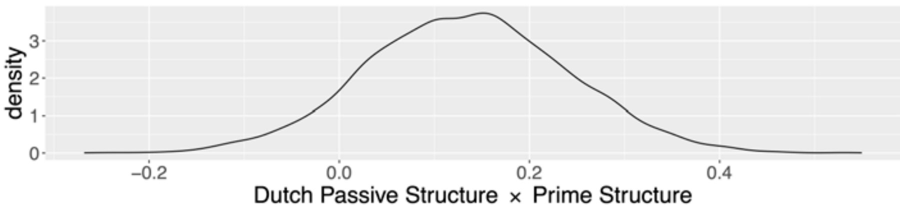



**Figure 3.5:** Posterior distribution of the estimate for the interaction between DUTCH PASSIVE STRUCTURE and PRIME STRUCTURE.

### 3.4.5 Discussion

The results of our pair of priming experiments using Dutch-English models show a clear and strong priming effect between verb-medial English transitives and both verb-final and verb-medial Dutch transitives. We therefore provide support for the viability of implicit learning as an account of experimental findings of cross-language structural priming between structures with different word order. However, our combined analysis does not show that the priming effect was stronger for structures that share word order (verb-medial Dutch-English), than for structures that do not (verb-final Dutch-English). This is not in line with behavioural results reported by Chen et al. (2013).

How can our finding of cross-language priming without identical word order be explained? We speculate that this is possible for the structures under investigation because Dual-path predicts sentences word by word. Connection weights are therefore adjusted after a word is predicted wrongly rather than after an entire sentence is predicted wrongly. If the prime sentence, for example, is a passive sentence that starts with the patient role: "*a bottle is broken by the father / een fles wordt door de vader gebroken (a bottle is by the father broken)*", and the model would wrongly predict an active sentence: "*the father breaks a bottle / de vader breekt een fles*", then error would occur when the model predicts the noun phrase that expresses the agent role "*the father / de vader*". Since learning is turned on in the model during processing of the prime sentence, the connection weights that bias towards a passive sentence would then be strengthened. This, in turn, would make the production of both English and Dutch passives more likely, because both those passives start with a noun phrase that expresses the patient role. Only after that noun phrase does word order differ in verb-medial English and verb-final Dutch passives. Of course, this account of what occurs in the model needs to be verified by inspecting the connection weights in the model.

Our results contribute to distinguishing between the error-driven implicit learning account of priming that is implemented in the Dual-path model and the hybrid account implemented in the model by Reitter et al. (2011). Our model shows priming to occur between transitives with different word order, while their model, in contrast, predicts identical word order to be a requirement for cross-language structural priming.

## 3.5 Indonesian – Verb-medial Dutch (Experiment 3)



As for example Ortega (2019) argued, generalizable insight into multilingualism requires us to study multilingual populations that extend beyond the typical participant group of undergraduate college students. It has also been argued that generalizability of findings in cognitive science is hindered by the over-reliance on English (Blasi, Henrich, Adamou, Kemmerer, & Majid, 2022). These criticisms also generally apply to studies on cross-language structural priming. Such studies often involve pairs of languages that are relatively closely related, where both languages are Indo-European in most cases and one of those languages is English. However, some studies show structural priming between languages that are not closely related such as Korean and English (Shin & Christianson, 2009).

We explore whether the findings of Experiment 1 generalize to a pair of languages that are not closely related and do not include English. We implemented an Indonesian-Dutch version of the model to simulate a cross-language priming experiment. In these two languages, passive voice is also expressed differently in that only Indonesian has a verb prefix for passive voice (see Section 3.5.1.2).

### 3.5.1 Method

#### 3.5.1.1 Exploratory and confirmatory experiments

We first conducted exploratory simulations and then performed a preregistered confirmatory experiment[10]. Compared to the exploratory experiment, for the confirmatory experiment we generated new experimental trials and trained a new, larger set (120 vs. 40) of simulated participants, with more variability in the balance between the two languages, and a 60%-40% bias towards actives versus passives instead of balanced transitives, which is more in line with the skew toward actives in natural language. Further,

[10] See the preregistration here: `https://aspredicted.org/nu3ce.pdf`

we used an adjusted version of the Dutch artificial language. Where the past participle (e.g., "*gebroken*") was at first provided to the model with a suffix (e.g., "*breken -vdw*") it was later provided with a prefix (e.g. "*vdw- breken*", see Example 2a). Finally, a somewhat different analysis was performed on the results, i.e., a frequentist analysis in Julia for the confirmatory analysis vs. a Bayesian analysis in R for the exploratory analysis. The motivation for the different analysis was not specific to the current experiment. Rather, it was motivated by the high computational requirements of Bayesian analyses in R with appropriate sensitivity analyses compared to frequentist analyses in Julia, combined with the current lack of a consensus in the literature on how to conduct those analyses (Van Doorn, Aust, Haaf, Stefan, & Wagenmakers, 2023).

Our analysis of the new simulated experiment reveals the same pattern of results for Indonesian – Dutch as for Spanish – English and Dutch – English, and the preregistered simulated experiment confirmed the exploratory experiment's results. Below, we report only the results of confirmatory experiment.

#### 3.5.1.2 Artificial languages

Before we could train model instances, we designed artificial versions of Indonesian and Dutch. This involves selecting the languages' syntactic constructions and vocabularies. The two artificial languages[11] have the same twelve sentence types: Animate intransitive, Animate with-intransitive, Inanimate intransitive, Locative, Transitive (active or passive), Cause-motion, Transfer dative (in prepositional object (PO) form), Benefactive dative (in PO form), Benefactive transitive, State-change, and Locative alternation[12]. The two languages together have 244 unique lexical items. The categories of words and morphemes in the artificial languages reflect those that occur in these sentence types in Dutch and Indonesian. Therefore, both languages had nouns, pronouns, verbs, adjectives, and prepositions. Only the Dutch lexical items also included articles, auxiliary verbs, and morphemes that indicate verb inflection for tense and aspect such as a past tense marker ('-ver', see Example 1a). Only the

[11] The files required to generate the artificial language input, the priming experiment input, and the code for the analysis can be found here: `https://osf.io/w2p7m/`

[12] English examples for these sentence types can be found in Chang et al. (2006)

Indonesian lexical items included a prefix for passive voice ('di-', see Example 2b). The message semantics contain 121 concepts, and 7 thematic roles.

1. Active (English: The father broke the bottle.):

   (a) Dutch: de vader breken -ver de fles .
   X = def, FATHER;
   ACTION-LINKING = BREAK;
   Y = def, BOTTLE;
   EVENT-SEM = X:1, Y:0.75, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = nl

   (b) Indonesian: ayah istirahat botol .
   [...];
   EVENT-SEM = X:1, Y:0.75, [...];
   TARGET-LANG = id

2. Passive (English: The bottle is broken by the father.):

   (a) Dutch: de fles wordt vdw- breken door de vader .
   [...];
   EVENT-SEM = X:0.75, Y:1, [...];
   TARGET-LANG = nl

   (b) Indonesian: botol di- istirahat oleh ayah .
   [...];
   EVENT-SEM = X:0.75, Y:1, [...];
   TARGET-LANG = id

### 3.5.2 Simulated priming experiment

#### 3.5.2.1 Simulated participants



We trained 120 simulated participants. They varied in how successfully they learned the artificial languages. The meaning accuracy scores (i.e. percentage of grammatically correct sentences that convey the target message without any additions, over all test sentences) varied from 7.05% to 90.55% with a mean of 67.73%. The percentage of grammatically correct sentences for these models varied from 80.65% to 99.9%, with a mean of 98.13%. All simulated participants were included in the analysis. However, we only include correctly produced sentences in the analysis (see Section 3.5.3), which means that simulated participants that produce more correct sentences contribute more to the analysed data.

#### 3.5.2.2 Experimental trials

Independent of training and test sets, a single set of experimental trials was generated that was used to perform the priming experiment on all simulated participants. Each trial consisted of a combination of a unique prime sentence and a unique target message without any semantic overlap in their verb, agent, and patient. With two levels for LANGUAGE COMBINATION (between- or within-language) and two levels for PRIME LANGUAGE, we had four possible combinations of prime- and target-language: Indonesian – Indonesian, Dutch – Dutch, Dutch – Indonesian, and Indonesian – Dutch. We had equal numbers of these language combinations, and therefore equal numbers of within- and cross-language trials. We also had equal numbers of trials with active and passive primes, and of trials with active- and passive-bias target-messages. The two levels for PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS combine for 16 conditions in total. We had 50 prime-target combinations that all occurred in each of the 16 different conditions. Each experiment thus consisted of 800 trials.

#### 3.5.2.3 Procedure

The priming experiment was performed on the simulated participants after 20 training epochs. As was done in Experiment 1 and 2, we presented the models with prime sentences without a message, with learning turned on in the model. After each prime, a response was elicited from the model by presenting it with a target message. We use a binary dependent variable that indicates whether the sentence structure that the model produced was passive or active.

To control for trial order effects, it is common in cross-language structural priming experiments (and many other psycholinguistic experiments) to (pseudo-)randomize trial order across participants (e.g., Hartsuiker et al., 2004). We used a simpler, but more rigorous method to reach the same end in our simulated experiments: After each trial, the connection weights were reset to the values they had before starting the priming experiment. The state in which the model encounters each trial was thus the same for all trials. Hence, there was no between-trial priming and no need to (pseudo-)randomize trial order across simulated participants.

### 3.5.3 Results

Following Experiment 1 and 2, our analysis only included responses that correctly conveyed the target message. However, we disregarded errors involving definiteness of articles or missing periods. Consequently, we included 51% of the responses on cross-language trials, and 44% on within-language trials. As visualised in Figure 3.6, for cross-language trials, 47.83% of sentences were passives after a passive prime, while 38.95% of sentences were passive after an active prime. For within-language trials, 53.47% of sentences were passives after a passive prime, while 31.92% of sentences were passive after an active prime. This figure also shows that by varying model parameters, we successfully created individual differences between the simulated participants in terms of the strength (and sometimes even direction) of structural priming.

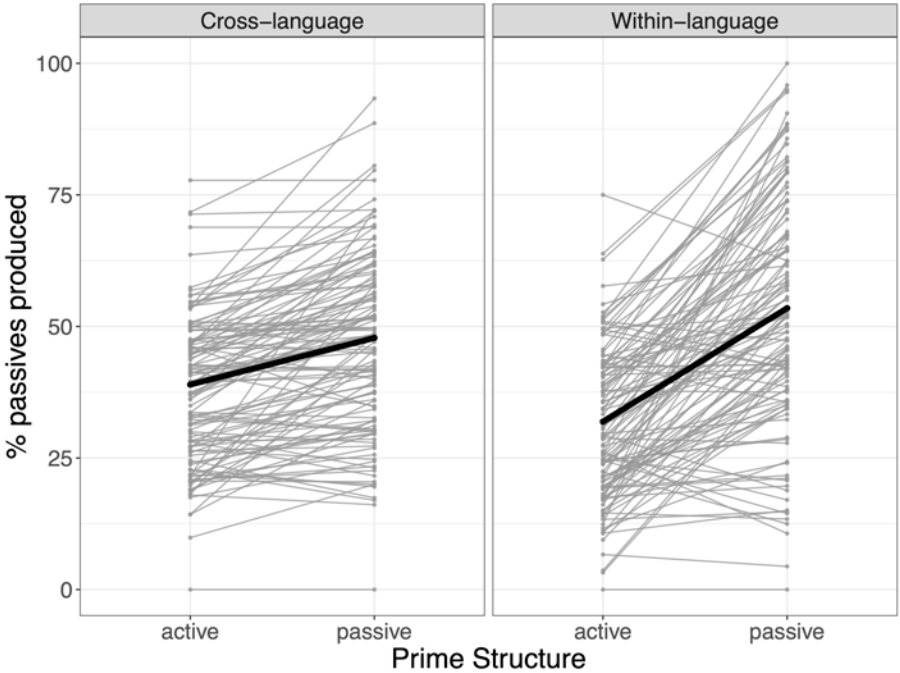



**Figure 3.6:** Percentage of passive target responses in Experiment 3 (Indonesian – Verb-medial Dutch) after either an active or a passive prime, for cross-language (left panel) and within-language trials (right panel). Thick black lines visualise the priming effect across all trials. Thin grey lines show the same for each simulated participant.

### 3.5.4 Analysis

We analyzed the data from our experiment using logistic mixed-effects models, as implemented in MixedModels.jl (Bates et al., 2013, version 4.22.2) in Julia (Bezanson, Edelman, Karpinski, & Shah, 2017, version 1.8). The model predicts a binary dependent variable, IsPassive, that indicates whether the model produced a passive (1), or active (0) sentence structure. In addition to the predictors of interest, LanguageCombination (Cross-language (0), Within-language (1)) and PrimeStructure (Active = −0.5, Passive = 0.5), the model includes two other contrast-coded predictors: Target-messageBias (Active = −0.5, Passive = 0.5) and PrimeLanguage (Indonesian = −0.5, Dutch = 0.5). We fit random intercepts for items and model participants, and by-participant random slopes for LANGUAGECOMBINATION, PRIMESTRUCTURE, and their interaction.

**Table 3.7:** Fixed effects summary for the logistic mixed-effects model ($N = 48,121$) for Experiment 3 (Indonesian – Verb-medial Dutch): estimates with 95% bootstrapped confidence intervals and $p$-values for each predictor.

| Predictor | Est. | 95% CI | $p$-value |
|---|---|---|---|
| INTERCEPT | −0.27 | [−0.48, 0.00] | 0.04 |
| PRIMESTRUCTURE | 0.65 | [0.46, 0.79] | < 0.001 |
| LANGUAGECOMBINATION | 0.16 | [−0.08, 0.39] | 0.22 |
| PRIMELANGUAGE | −0.12 | [−0.19, 0.03] | 0.01 |
| TARGET-MESSAGEBIAS | 3.24 | [2.98, 3.16] | < 0.001 |
| LANGUAGECOMB. × PRIMESTRUCT. | 0.69 | [0.44, 0.89] | < 0.001 |

The analysis results are summarized in Table 3.7. The positive estimate for PRIMESTRUCTURE, with a confidence interval far from zero, shows a clear priming effect at the reference level (cross-language) of LANGUAGECOMBINATION. This indicates strong evidence for cross-language priming in the Dual-path model. The positive estimate for the interaction between LANGUAGECOMBINATION and PRIMESTRUCTURE, with a confidence interval not crossing zero, indicates stronger within-language than the cross-language priming in the model.

### 3.5.5 Discussion

Our simulation reveals a clear and strong cross-language structural priming effect. We also find slightly stronger within- than cross-language structural priming. We thus show that findings of these effects for more closely related languages (Experiment 1 and 2) generalize to a pair of languages that not only differ typologically, but also express passive voice differently. An obvious limitation in modeling typological differences between languages with Bilingual Dual-path is that it does not accommodate phonology, and the simulated differences are therefore restricted to morpho-syntactic differences such as the use of determiners, verb inflection and word order.

When prediction error occurs while processing a passive prime sentence in one language, implicit learning strengthens the connections associated with the prime's syntactic structure. This not only makes the occurrence of a sentence in passive voice more expected in the same language, but also in the other language, even though passive voice is expressed differently in the two languages.

Although cross-language structural priming in humans has been demonstrated for pairs of unrelated languages such as Korean-English and Mandarin Chinese-English, it has not been demonstrated for Indonesian-Dutch, the language pair that we investigated. Therefore, it remains to be determined whether our results are in line with how Indonesian and Dutch syntax interact in humans.

An experiment that determines whether simulated and behavioral results correspond will likely require more effort than testing participants from the common group of undergraduate college students who are speakers of a language pair that occurs frequently, with one of those languages being English. Having performed computational simulations beforehand, will ensure that findings of such an experiment can be interpreted in terms of their theoretical implications, at least with regards to an implicit learning account of cross-language structural priming.

## 3.6 Conclusion

Across the three experiments, we see clear and strong within-language priming effects, which confirm earlier findings, and similarly clear and strong cross-language priming effects, that provide further support for error-driven implicit learning as a viable underlying mechanism of structural priming. The finding is consistent with our expectation that the model would learn syntactic representations that abstract away from the target language sufficiently to enable cross-language structural priming.

Experiment 2a revealed priming between structures that do not share word order. This is in line with a number of results from behavioural experiments, and it sets the implicit learning account apart from the hybrid account proposed by Reitter et al. (2011), which predicts that identical word order is a requirement for structural priming.

The analyses of the three experiments also provide support for within-language priming being stronger than cross-language priming. In Experiment 2a, where the

Dutch and English passives did not share word order, there was a slightly weaker priming effect than in Experiment 2b. However, a combined analysis of the cross-language trials from these two experiments revealed a small but not statistically reliable difference in the strength of the cross-language priming effect between the two Dutch-English experiments. The evidence we find for stronger within-language than cross-language priming is consistent with the results of behavioural studies that also report evidence for such a difference (Bernolet et al., 2013; Cai et al., 2011). Other studies, however, report results in which the difference is not significant (Hartsuiker et al., 2016; Kantola & van Gompel, 2011; Schoonbaert et al., 2007).

The results of the Experiment 3 show that the pattern of findings in the model of cross-language priming effects between more closely related languages generalize to a pair of languages that not only differ typologically, but also express passive voice differently.

# Chapter appendix



## 3.A Supplementary analyses

In this appendix we report on supplementary analyses that are the same as the analyses in Experiments 1 and 2 of this chapter except that they include all 120 simulated participants instead of only the 80 simulated participants with the highest accuracy at test. Extending the analyses to all 120 simulated participants leads to the same pattern of results. The results of the supplementary analyses are summarised in Table 3.A.1 for Experiment 1, in Table 3.A.2 for Experiment 2a, in Table 3.A.3 for Experiment 2b, and in Table 3.A.4 for the combined analysis of cross-language trials from both experiments.

**Table 3.A.1:** Summary of the fixed effects in Experiment 1 with all 120 simulated participants (N = 55,699). For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive ($P$(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIMESTRUCTURE).

| Predictor | Est. | 95% CrI | $P$(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | 0.48 | [0.13, 0.85] | 0.99 |
| PRIME STRUCTURE | 0.89 | [0.62, 1.16] | 1.00 |
| LANGUAGE COMBINATION | 0.11 | [−0.05, 0.28] | 0.91 |
| PRIME LANGUAGE | 0.25 | [0.14, 0.36] | 1.00 |
| TARGET-MESSAGE BIAS | 9.25 | [9.05, 9.45] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.85 | [0.57, 1.13] | 1.00 |

**Table 3.A.2:** Summary of the fixed effects in Experiment 2a with all 120 simulated participants (N = 51,063). For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive ($P$(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIMESTRUCTURE).

| Predictor | Est. | 95% CrI | $P$(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | −0.31 | [−0.62, 0.00] | 0.03 |
| PRIME STRUCTURE | 1.23 | [0.93, 1.53] | 1.00 |
| LANGUAGE COMBINATION | −0.10 | [−0.25, 0.05] | 0.10 |
| PRIME LANGUAGE | 0.18 | [0.09, 0.27] | 1.00 |
| TARGET-MESSAGE BIAS | 7.44 | [7.29, 7.59] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.76 | [0.53, 1.00] | 1.00 |

**Table 3.A.3:** Summary of the fixed effects in Experiment 2b with all 120 simulated participants (N = 67,450). For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive ($P$(Est. $>$ 0)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, LANGUAGE COMBINATION, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between LANGUAGE COMBINATION and PRIMESTRUCTURE).

| Predictor | Est. | 95% CrI | $P$(Est. $>$ 0) |
|---|---|---|---|
| INTERCEPT | 0.39 | [0.10, 0.69] | 0.99 |
| PRIME STRUCTURE | 1.34 | [1.07, 1.61] | 1.00 |
| LANGUAGE COMBINATION | −0.06 | [−0.17, 0.05] | 0.16 |
| PRIME LANGUAGE | 0.51 | [0.44, 0.58] | 1.00 |
| TARGET-MESSAGE BIAS | 7.35 | [7.23, 7.47] | 1.00 |
| LANGUAGE COMBINATION × PRIME STRUCTURE | 0.33 | [0.14, 0.51] | 1.00 |

**Table 3.A.4:** Summary of the fixed effects in combined analysis of cross-language trials from Experiments 2a and 2b with all 120 simulated participants (N = 63,332). For each predictor are shown its estimate (Est.) with 95% Bayesian credible interval (CrI) and the posterior probability that the estimate is positive (*P*(Est. $> 0$)). Estimated are: log-odds (for the INTERCEPT), log-odds ratios (for the PRIME STRUCTURE, DUTCH PASSIVE STRUCTURE, PRIME LANGUAGE, and TARGET-MESSAGE BIAS predictors), and a ratio of log-odds ratios (for the interaction between DUTCH PASSIVE STRUCTURE and PRIME STRUCTURE).

| Predictor | Est. | 95% CrI | *P*(Est. $> 0$) |
|---|---|---|---|
| INTERCEPT | −4.59 | [−4.84, −4.32] | 0.00 |
| PRIME STRUCTURE | 1.21 | [1.01, 1.43] | 1.00 |
| DUTCH PASSIVE STRUCTURE | 0.69 | [0.58, 0.80] | 1.00 |
| PRIME LANGUAGE | 0.32 | [0.25, 0.39] | 1.00 |
| TARGET-MESSAGE BIAS | 7.04 | [6.93, 7.15] | 1.00 |
| DUTCH PASSIVE STRUCTURE × PRIME STRUCTURE | 0.12 | [−0.03, 0.26] | 0.93 |

# 4

# Simulating proficiency and exposure effects on cross-language structural priming in simultaneous bilinguals

**Based on:** Khoe, Y. H., Kootstra, G.J., Schoonen, R., Frank, S. (2021). Simulating proficiency and exposure effects on cross-language structural priming in simultaneous bilinguals. In Stewart, T. C. (Ed.), *Proceedings of the 19th International Conference on Cognitive Modelling*, (pp. 150-156).

http://acs.ist.psu.edu/papers/ICCM2021Proceedings.pdf#page=158

## Abstract

Bilingual speakers are more likely to use a syntactic structure in one language if they have recently encountered that same structure in another language. This cross-language structural priming effect is predicted to be positively modulated by second language proficiency according to a developmental account by Hartsuiker and Bernolet (2017). We propose to extend this account from *sequential* bilinguals to *simultaneous* bilinguals. In this latter group, syntactic structures develop in parallel and can integrate from the onset. Therefore, we do not expect proficiency or other measures of development, such as exposure, to modulate cross-language structural priming in these bilinguals.

In simulated cross-language structural priming experiments, we explored how proficiency affects priming of transitives. We use an implicit learning model of sentence production to model the simultaneous English-Spanish bilinguals in these simulations. Furthermore, we investigated whether the priming effect is modulated by exposure to the non-dominant language, which only Kutasi et al. (2018) also analyzed. We found no evidence for any modulating effects for either proficiency or exposure, which is in line with the previously reported behavioral result of Kutasi et al. (2018). Together, our modeling results and Kutasi et al.'s (2018) behavioral results support an extended version of the developmental account of cross-language structural priming that predicts a modulating effect of proficiency in *sequential* bilinguals, but not in *simultaneous* bilinguals.

## 4.1 Introduction

It is still an open question how second language (L2) proficiency affects cross-language structural priming. Hartsuiker and Bernolet (2017) have hypothesized that as L2 learners become more proficient, their L2 syntactic representations become more integrated with the representations that they already have for their native language (L1). In this developmental account, the increased integration will then result in increased cross-language structural priming.



In a number of cross-language structural priming studies, proficiency or amount of exposure to the L2 were investigated as predictors of the strength of the priming effect. In four cases, increased cross-language structural priming was found for more proficient participants. The results presented by Bernolet et al. (2013) revealed a positive effect of proficiency on the strength of priming between Dutch and English genitives. A reanalysis by Hartsuiker and Bernolet (2017) of an experiment performed by Schoonbaert et al. (2007) also revealed that cross-language priming of datives in Dutch-English bilinguals was stronger for participants who were more proficient in their L2. Similarly, Favier et al. (2019) found that proficiency positively modulated priming of datives and passives from Irish to English. In their investigation of priming between Korean and English transitives, Hwang, Shin, and Hartsuiker (2018) found a priming effect that increased in magnitude as participants were more proficient in their L2, English. In contrast, three other studies did not yield evidence that proficiency modulates priming. The results reported by Hartsuiker et al. (2016) for priming of relative clause attachment and of datives in multilingual speakers of Dutch (L1), French (L2), English (L2), and German (L2) did not reveal such an effect. Similarly, the results reported by Kutasi et al. (2018) for English and Gaelic transitives did not reveal any effect of either proficiency or exposure. Huang et al. (2019) also found no correlation between self-rated proficiency and the priming effect of datives in trilingual speakers of Mandarin, Cantonese, and English.

These conflicting results might be partly explained by considering the type of bilinguals that were involved in the studies. Whereas all but one of the participants in Kutasi et al.'s (2018) study were *simultaneous* bilinguals, the participants in the other studies were all or in majority *sequential* bilinguals. In our interpretation of the developmental account by Hartsuiker and Bernolet (2017), proficiency is expected to affect cross-language structural priming in *sequential* bilinguals, who start learning a second language after they have acquired their L1, but not in *simultaneous* bilinguals, who acquire their two languages at the same time. These simultaneous bilinguals would develop syntactic representations for both languages at the same time, which could integrate from the onset. The results of the study by Kutasi et al. (2018) is in line with this extended account, as they did not reveal an effect of either proficiency or exposure in the non-dominant language on cross-language structural priming.

While the number of behavioral studies on the effect of proficiency on cross-language structural priming is growing, proficiency differences have not been studied using implemented models of cross-language structural priming. In the simulations in Chapter 3, the aim was to model balanced simultaneous bilinguals, and the models were therefore trained using approximately equal numbers of sentences in the two languages, that varied only minimally.

In this chapter we explore the effect of proficiency and exposure in the non-dominant language on cross-language structural priming in simultaneous bilinguals, whom we model using an implicit learning model of sentence production. We do this by varying the amount of input in the two different languages that the model receives during training. We then perform cross-language structural priming experiments with these model instances as participants. We analyse the results of these experiments to determine whether proficiency or exposure in the non-dominant language modulate cross-language structural priming in the model.

## 4.2 Method

### 4.2.1 Model

We trained instances of the Bilingual Dual-path model[1] of sentence production (Figure 2.1) on miniature versions of English and Spanish to serve as simulated participants in cross-language priming experiments.

The training input to the model consists of sentences in two artificial languages that are paired with messages that encode their meaning (see examples below, in Section 4.2.1.1). The model instances receive input in both languages from the start of training to simulate simultaneous English-Spanish bilinguals, who start acquiring both English and Spanish from infancy.



#### 4.2.1.1 Artificial languages

The artificial versions of English and Spanish[2] that we used include the same nine sentence types for each language: Animate intransitive, Animate with-intransitive, Inanimate intransitive, Locative, Transitive (in active or passive form), Cause-motion, Benefactive transitive, State-change, and Locative alternation. Examples for these sentence types can be found in Chapter 3. The two languages together have 275 unique lexical items. In addition to nouns, verbs, adjectives, determiners, and prepositions, these lexical items include inflectional morphemes such as a past tense marker (Spanish: '-pas'; English: '-pst') and a past participle marker (Spanish: '-prf'; English: '-par'). The message semantics contain 121 concepts and 7 thematic roles. Only singular verbs, pronouns, nouns, and adjectives were used. Verbs and pronouns were always in third person form.

Of the transitives in our artificial languages, 75% were actives and 25% were passives. This skew in favor of actives is more in line with the frequencies of these constructions

[1]The version of the Bilingual Dual-path model we used here can be downloaded from: `https://gitlab.com/yhkhoe/bilingual-dual-path/-/tree/ICCM2021`

[2]The files that the model requires to generate the artificial language input, and the input for the priming experiment can be found here: `https://github.com/khoe-yh/cross-lang-struct-priming`

in natural language than the balanced frequencies of actives and passives that we used in Chapter 3.

In the training and test input, any message that can be expressed using two different syntactic structures has a strong bias towards one of those structures. This was implemented by creating differences in activation of thematic roles based on how each structure emphasizes those roles in the sentence. Biasing towards an active sentence (1, 2), for example, was done by giving the agent a higher activation (X:1) than the patient (Y:0.5 or Y:0.75). In the same way, a bias towards a passive sentence (3, 4) was achieved with a higher activation for the patient (Y:1), than for the agent (X:0.5 or X:0.75). In the priming experiment, we gave the de-emphasized roles in target messages an activation of 0.75.

1. Spanish Active: el padre romper -pas la botella .
   X = def, FATHER, M;
   ACTION-LINKING = BREAK;
   Y = def, BOTTLE;
   EVENT-SEM = **X:1, Y:0.5**, PAST, SIMPLE, ACTION-LINKING;
   TARGET-LANG = es

2. English Active: the father break -pst the bottle .
   [...];
   EVENT-SEM = **X:1, Y:0.5**, [...];
   TARGET-LANG = en

3. Spanish Passive: la botella es romper -prf por el padre .
   [...];
   EVENT-SEM = **X:0.5, Y:1**, [...];
   TARGET-LANG = es

4. English Passive: the bottle is break -par by the father .
   [...];
   EVENT-SEM = **X:0.5, Y:1**, [...];
   TARGET-LANG = en

#### 4.2.1.2 Model training and testing

We trained 120 model instances that function as simulated participants in our experiments. To simulate proficiency differences in the English-Spanish models, we trained the models with a percentage of sentences in Spanish, the non-dominant language, sampled from a truncated normal distribution (lower bound: 0%, upper bound: 50%) with a mean of 35%, and a standard deviation of 15, and the rest was in English. A set of 8,000 unique message-sentence pairs was generated for each model participant. 80% of these sentences were used for training, while 20% were set aside for testing the accuracy of the model. Following Chang et al. (2006), the message was excluded from 25% of training pairs. The models iterated over their training sets 16 times. After each of these 16 epochs, model accuracy was tested using the test set. The training set was shuffled at the beginning of each epoch.



#### 4.2.1.3 Model configuration

Differences between individual simulated participants were also created through small variation in model parameters. The number of hidden-layer units was sampled from a uniform distribution between 58 and 62, while the number of compress layer units was sampled from a uniform distribution between 38 and 42. The fixed weight value for concept–role connections was sampled from a uniform distribution between 13 and 17.

**Table 4.1:** Meaning accuracy, syntactic accuracy, and input in the non-dominant language (Spanish) for the 120 simulated participants in our experiment.

| | Mean | Standard Deviation |
|---|---|---|
| Meaning accuracy | 61.3% | 19.4 |
| Syntactic accuracy | 96.1% | 6.5 |
| Input | 29.8% | 11.3 |

### 4.2.2 Priming experiment

#### 4.2.2.1 Simulated participants



Table 4.1 gives an overview of measures of proficiency and exposure for the non-dominant language (Spanish) of the 120 simulated participants in our experiment. We operationalized proficiency in the non-dominant language as either syntactic accuracy or meaning accuracy in that language. Syntactic accuracy was measured as the percentage of sentences out of all test sentences for which all the words had the correct part of speech. Meaning accuracy was measured as the percentage of syntactically accurate sentences that convey the target message without any additions. Exposure to the non-dominant language was operationalized as the percentage of sentences in the training input in that language.

The standard deviations of these measures suggest that the heterogeneity in our sample of simulated participants is comparable to that in the participant samples of Kutasi et al. (2018) and Favier et al. (2019). Both studies report self-rated proficiency measures on a 7-point scale. The standard deviations for these measures ranged from 0.51 to 1.00 in the study by Kutasi et al. (2018), and from 0.61 to 1.12 in the study by Favier et al. (2019).

#### 4.2.2.2 Experimental trials

In addition to the training and test sets, we generated a single set of experimental trials that was used to perform the priming experiment on all of the model participants. Each trial consisted of a combination of a unique prime sentence and a unique target message that did not have any semantic overlap in terms of their verb, agent, and patient. Following Kutasi et al. (2018), we only used prime sentences in the non-dominant language, which in our case was Spanish. We had equal numbers of trials with active and passive primes, and equal numbers of trials with active- and passive-bias target messages. We had 50 prime-target combinations that all occurred as each of the 4 different trial types. Each experiment thus consisted of 200 trials.

#### 4.2.2.3 Procedure

The priming experiment was performed on the models after 16 training epochs. As was done by Chang et al. (2006) and Chang et al. (2015), we presented the models with prime sentences without a message, while learning was turned on in the model. After each prime, a response was elicited from the model by presenting it with a target message.

We aimed to simulate a cross-language structural priming effect that is similar in strength to what is found experimentally in humans. Since the strength of the effect in the model is largely determined by the learning rate, we used a range of different learning rates. In Chapter 3, a learning rate of 0.2 was used during the experiment. This resulted in priming effects that were stronger than such effects found in behavioral experiments. For our study, we therefore used learning rates between 0.02 (the learning rate at the end of training) and 0.10 (the learning rate at the beginning of training).



After each trial, the connection weights were reset to the values they had before starting the priming experiment. The state in which the model encounters each trial was thus the same for all of the trials, hence, there was no between-trial priming or any other learning effect during the experiment. This means that we did not need to (pseudo-)randomize the order of the trials across model participants.

## 4.3 Results

### 4.3.1 Descriptive results

Our analyses only included responses that correctly expressed the target message, with either an active or a passive structure. However, we disregarded errors involving definiteness of articles or missing periods. Table 4.2 shows the percentage of responses that was included on the basis of these criteria for each of the three learning rates at which the experiment was run. The table also shows the percentage of these responses that were passives after a passive prime or after an active prime.

**Table 4.2:** Percentage of included responses, and percentage of passive sentences produced after a passive prime or after an active prime, at learning rates of 0.02, 0.06 or 0.10.

| | Learning rate | | |
|---|---|---|---|
| | 0.02 | 0.06 | 0.10 |
| Responses included | 52.0% | 51.0% | 51.7% |
| Passives after passive prime | 38.1% | 38.2% | 38.6% |
| Passives after active prime | 37.9% | 37.8% | 37.4% |



### 4.3.2 Bayes Factor analyses

We analyzed the data from our experiment with Bayesian logistic mixed-effects models, with a logit link function, using the function brm from the package brms (Bürkner, 2017, 2018, version 2.12.0) in R (R Core Team, 2018a, version 3.5.1). These analyses were not pre-registered and should therefore be considered exploratory.

The models predicted a binary dependent variable, IS PASSIVE, that indicated whether the sentence that the model produced was passive (1), or not (0). The null model included three centered continuous predictors: MEANING ACCURACY, SYNTACTIC ACCURACY, and INPUT, and two contrast-coded predictors PRIME STRUCTURE (Active = −0.5, Passive = 0.5), and TARGET-MESSAGE BIAS (Active = −0.5, Passive = 0.5). We fit random intercepts for model participants and items, as well as by-participant random slopes for PRIME STRUCTURE. The alternative models only differed from the null model in including an interaction between PRIME STRUCTURE and either MEANING ACCURACY, SYNTACTIC ACCURACY, or INPUT. We computed Bayes Factors that compare the null model to these alternative models.

We calculated Bayes Factors using bridge sampling (Bennett, 1976; Meng & Wong, 1996; Gronau et al., 2017), with four chains and 8000 iterations, including a warm-up phase of 2000 iterations. Because an uninformative prior for the predictor of interest can make a Bayes Factor biased towards the null model (Lee & Wagenmakers, 2014), we report Bayes Factors across four different values of the standard deviation ($\sigma$) for the prior of the interaction of interest (Normal(0, $\sigma$)), ranging from a value appropriate for an informative prior (i.e., $\sigma$ = 0.25) to a value appropriate for a regularizing prior (i.e., $\sigma$

**Table 4.3:** Bayes Factors that compare models including interactions between each of the three predictors of interest and Prime Type with a null model without any such interaction, for priming experiments with a learning rate of 0.02, 0.06, or 0.10, where the prior for the interaction had a standard deviation of either 0.5 or 1. A Bayes Factor smaller than 1 favors the null model whereas a Bayes Factor larger than 1 favors the alternative model that includes an interaction.

| Learning Rate | Standard Deviation | | | |
|---|---|---|---|---|
| | 0.25 | 0.5 | 0.75 | 1 |
| | Meaning accuracy | | | |
| 0.02 | 0.118 | 0.060 | 0.041 | 0.028 |
| 0.06 | 0.221 | 0.097 | 0.070 | 0.054 |
| 0.10 | 0.109 | 0.053 | 0.036 | 0.030 |
| | Syntactic accuracy | | | |
| 0.02 | 0.249 | 0.119 | 0.084 | 0.066 |
| 0.06 | 0.360 | 0.173 | 0.120 | 0.096 |
| 0.10 | 0.279 | 0.159 | 0.097 | 0.071 |
| | Input | | | |
| 0.02 | 0.146 | 0.075 | 0.051 | 0.039 |
| 0.06 | 0.140 | 0.058 | 0.046 | 0.030 |
| 0.10 | 0.133 | 0.077 | 0.047 | 0.035 |

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= 1). Regularizing priors (Normal(0,1)) were used for all other predictors in our models. These priors give a minimal amount of information with the objective of yielding stable inferences. Prior means were 0, and did thus not bias towards specific effects. The only exception to this was the TARGET-MESSAGE BIAS predictor for which we excluded negative values by using a prior with a Gamma distribution (Gamma(1, 0.5)).

Table 4.3 shows that the Bayes Factors are all smaller than 1, and thus provide evidence in favor of the null model. Based on the scale proposed by Jeffreys (1998), we interpret this evidence as ranging from anecdotal to very strong. As expected, when a smaller standard deviation is used for the prior, the Bayes Factors are mostly closer to 1, and thus provide less conclusive evidence for the null model. The Bayes Factors do not suggest a clear effect of learning rate on the strength of the evidence for the null model.

**Table 4.4:** Summary of the fixed effects in the Bayesian logistic mixed-effects null models with different learning rates ($N$ =14.908, 14,828, and 14,640, for experiments with learning rates of 0.02, 0.06, and 0.10 respectively).

| Predictor | Estimate, 95% CrI | | | P(Est. > 0) | | |
|---|---|---|---|---|---|---|
| Learning rate | 0.02 | 0.06 | 0.10 | 0.02 | 0.06 | 0.10 |
| INTERCEPT | 0.72 | 0.18 | 0.08 | 0.96 | 0.70 | 0.60 |
| | [−0.07, 1.57] | [−0.48, 0.86] | [−0.51, 0.68] | | | |
| PRIME STRUCTURE | 0.55 | 0.71 | 1.32 | 0.93 | 0.99 | 1.00 |
| | [−0.19, 1.30] | [0.10, 1.35] | [0.58, 2.05] | | | |
| TARGET-MESSAGE BIAS | 19.15 | 17.70 | 16.24 | 1.00 | 1.00 | 1.00 |
| | [16.73, 22.05] | [15.77, 19.98] | [14.68, 18.04] | | | |
| MEANING ACCURACY | −0.09 | −0.08 | 0.08 | 0.00 | 0.00 | 0.12 |
| | [−0.16, −0.03] | [−0.14, −0.02] | [−0.09, 0.02] | | | |
| SYNTACTIC ACCURACY | 0.03 | 0.12 | 0.08 | 0.99 | 0.92 | 0.83 |
| | [0.02, 0.38] | [−0.05, 0.29] | [−0.08, 0.23] | | | |
| INPUT | 0.03 | 0.06 | 0.02 | 0.79 | 0.96 | 0.70 |
| | [−0.05, 0.11] | [−0.01, 0.13] | [−0.04, 0.07] | | | |

### 4.3.3 Null model estimates

Because our exploratory analysis does not yield any evidence for modulating effects of proficiency or exposure on priming, we do not report estimates from the analyses that included interactions between PRIME STRUCTURE and any of our three predictors of interest. Instead, we provide a summary of the results from the null models for priming experiments with three different learning rates in Table 4.4. In line with our expectations, the estimates for the PRIME STRUCTURE predictor are higher for higher learning rates. The credible intervals for the PRIME STRUCTURE predictor contain only positive values at learning rates of 0.06 and 0.10, which indicates strong evidence for a priming effect. At a learning rate of 0.02, the credible interval that includes some negative values indicates weaker evidence for a priming effect.

## 4.4 Discussion

In this chapter, we explored whether proficiency or exposure modulate cross-language structural priming in simultaneous bilinguals, simulated using an implicit learning model of sentence production. Our results indicate anecdotal to strong evidence against such modulating effects in the model. This is in line with the results reported by Kutasi et al. (2018). Taken together, those behavioral results and our modeling results provide support for an extended version of the developmental account of cross-language structural priming (Hartsuiker & Bernolet, 2017) that not only predicts a modulating effect of proficiency in *sequential* bilinguals, but that also explicitly predicts the absence of such an effect in *simultaneous* bilinguals.



A limitation of our simulations lies in a difference between the languages and syntactic structures involved in our simulated experiments and those in the experiments that Kutasi et al. (2018) conducted. The main question that Kutasi et al. (2018) addressed in their study, was whether cross-language priming can occur for structures with different word order between languages. For this reason, they studied bilinguals who spoke English and Scottish Gaelic, for which active as well as passive word order is different. In contrast, the English and Spanish transitives in our experiments have the same word order between the two languages for both actives and passives. We could therefore come closer to simulating the results from Kutasi et al. (2018) by using the English-Dutch model reported on in Chapter 3 in which English passives are verb-medial, while Dutch passives are verb-final.

The participants that were involved in the other studies that investigated the possible modulating effect of proficiency on cross-language structural priming were sequential bilinguals. An obvious follow up to the study presented here is to simulate cross-language structural priming in these sequential bilinguals, and to determine whether proficiency or exposure does modulate priming in these simulations, as predicted by the developmental account of Hartsuiker and Bernolet (2017).

# 5

# A neural network model of event-related potentials in second-language syntax learning: simulating the response to syntactic violations and the role of cross-language syntactic transfer in this response

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https://repository.ubn.ru.nl/bitstream/handle/2066/301529/301529.pdf

**And:** Verwijmeren, S., Frank, S.L., Fitz, H., Khoe, Y. H. (2024). Simulating event-related potentials in bilingual sentence comprehension: syntactic violations and syntactic transfer. *Proceedings of the 22nd International Conference on Cognitive Modelling*

`https://repository.ubn.ru.nl/bitstream/handle/2066/309143/309143.pdf`

## Abstract

Event-related potentials (ERPs) are used to study how language is processed in the brain, including differences between first-language (L1) and second-language (L2) comprehension. In low-proficiency L2 learners, syntactic violations give rise to an N400, whereas a P600 ERP effect can be measured in more proficient L2 learners, indicating native-like processing. Cross-language similarity seems to be a factor that modulates effect sizes of such P600s. This manifests in a reduced P600 effect in response to a syntactic violation in the L2 when the syntactic feature involved is expressed differently in the two languages. Fitz and Chang (2019) proposed a theory where ERPs reflect learning signals that arise from mismatches in predictive processing. These signals are propagated across the language system to make future predictions more accurate. We test if this theory can account for the N400-to-P600 switch in late bilinguals and how the P600 depends on cross-language similarity, by implementing a model capable of simulating the N400 and P600.

First, we perform an experiment designed to elicit a P600 effect in simulated L2 learners as their learning progresses. Simulated Spanish-English participants showed similar ERP effects in their L2 (English) as human participants did in ERP studies. Over the course of L2 learning, simulated N400 size decreased while P600 size increased, as it does in humans.

Next, we use the model to simulate the P600 in response to three types of syntactic constructions differing in cross-language similarity. Simulated English-Spanish participants displayed a P600 when encountering constructions that are similar between the two languages, but a reduced P600 for constructions that differ between languages. This difference between the two P600 responses mirrors what has been observed in human ERP studies. Unlike human participants, however, simulated participants showed a small P600 response to constructions unique to the L2 (i.e., grammatical gender).

Our findings support the viability of error propagation as an account of ERPs, specifically of how these can change over L2 learning, and on the effects of syntactic transfer from L1 to L2.


5

## 5.1 Introduction

### 5.1.1 Event-related potentials in bilingualism



Electroencephalography is a technique for recording electrical voltage potentials produced by neural activity. Recorded potentials can be analyzed in relation to cognitive events, yielding interpretable patterns called event-related potentials (ERPs; Morgan-Short, 2014). ERP effects have been observed in response to syntactic violations in first language (L1) processing, as an increased positivity in the ERP waveform that starts around 600 ms after observing an anomalous word, as compared to its correct counterpart (Hagoort, Brown, & Groothusen, 1993; Osterhout & Mobley, 1995). This effect is called a P600. Another ERP effect is reliably elicited in response to a lexico-semantic violation. This effect, called an N400, is a negative voltage deflection around 400 ms after an anomalous word, as compared to a semantically appropriate word (Kutas & Hillyard, 1980).

#### 5.1.1.1 L2 learning

ERP research has been done to find out if L2 learners show similar ERP effects as native speakers for morpho-syntactic and lexico-semantic processing. Research has shown that L2 learners can show native-like ERP waveforms for L2 grammatical features that are present in their L1 as well as for features unique to their L2 (Morgan-Short, 2014). ERPs of L2 learners differing in proficiency suggest that as L2 learning progresses, learners develop from having no L2 grammatical knowledge to showing L1-like grammaticalization (McLaughlin et al., 2010). The observed ERP effects differ between studies. Some L2 learning studies that investigated syntactic processing found an N400 for learners with low proficiency and a P600 for learners with high proficiency, suggesting that L2 learners might rely more on lexical processing in early learning (Alemán Bañón, Fiorentino, & Gabriele, 2014; Antonicelli & Rastelli, 2022; Díaz et al., 2016; Esfandiari, Nilipour, Maftoon, & Nejati, 2021; Grey, 2022; Mickan & Lemhöfer, 2020; Nichols & Joanisse, 2019; Osterhout et al., 2008; Tanner et al., 2013; Tanner, Inoue, & Osterhout, 2014). Other related studies found a similar effect for proficiency but ERPs were biphasic at low proficiency levels, where the first phase of the ERP resembled an N400 followed by a second phase resembling a P600. With increasing proficiency, the amplitude of the N400 decreased and the P600 amplitude increased but ERP waveforms remained biphasic to a degree (Bian, Zhang, & Sun, 2021; Bowden, Steinhauer, Sanz, & Ullman, 2013; Caffarra, Molinaro, Davidson, & Carreiras, 2015; Esfandiari, Nilipour, Nejati, Maftoon, & Khosrowabadi, 2020; Grey, Sanz, Morgan-Short, & Ullman, 2018; McLaughlin et al., 2010; Morgan-Short, Steinhauer, Sanz, & Ullman, 2012; Morgan-Short, 2014; Pélissier, Krzonowski, & Ferragne, 2015). In the majority of studies, L2 proficiency was the most important factor determining ERP profiles (Antonicelli & Rastelli, 2022; Caffarra et al., 2015; McLaughlin et al., 2010; Morgan-Short, 2014).



#### 5.1.1.2 Cross-language similarity

While L2 proficiency is the most important factor determining ERP size during L2 processing (Antonicelli & Rastelli, 2022; Caffarra et al., 2015; McLaughlin et al., 2010; Morgan-Short, 2014), similarities and differences between the L1 and L2 often modulate the effect of proficiency. Some ERP studies showed reduced P600 effects, or no P600 effect, for syntactic features that are instantiated differently between languages (Antonicelli & Rastelli, 2022; Liu, Dunlap, Tang, Lu, & Chen, 2017; Morgan-Short, 2014), while others found P600 effects for syntactic L2 features regardless of the (dis)similarity between L1 and L2 (Caffarra et al., 2015; McLaughlin et al., 2010; Morgan-Short, 2014). There appears to be a complex influence of L1-L2 similarity. As is the case for L2 processing of syntactic features that are expressed similarly in the L1 and L2 (Foucart & Frenck-Mestre, 2011; McLaughlin et al., 2010; Morgan-Short, 2014), native-like L2 processing (i.e., showing a native-like P600 response) of syntactic features that are unique to the L2 is possible (Foucart & Frenck-Mestre, 2012; McLaughlin et al., 2010; Morgan-Short, 2014). But when a syntactic feature is present but expressed differently in the two languages, the P600 seems to be less sensitive to syntactic violation in the L2 (Sabourin & Stowe, 2008; Tokowicz & MacWhinney, 2005).

**Table 5.1:** Constructions containing syntactic violations with Spanish example sentences and their English translation. Words indicated with an asterisk are experimentally manipulated (here shown in the violation condition). Critical words are underlined. Table adapted from Tokowicz and MacWhinney (2005).

| Violated feature | Similarity | Example sentence Spanish | English translation |
|---|---|---|---|
| Tense | Similar | Su abuela *cocinando muy bien | His grandmother *cooking very well |
| Determiner gender | Unique | Ellos fueron a *un fiesta | They went to *a-MASC party |
| Determiner number | Different | *El niños están jugando | *The-SING boys are playing |



Tokowicz and MacWhinney (2005) presented native English speaking learners of L2 Spanish with Spanish sentences containing syntactic violations. There were three types of syntactic violations: verb-tense violation, determiner gender violation, and determiner number violation (see Table 5.1). A sentence with a *tense violation* contained a verb in the progressive tense without an auxiliary verb. The syntactic construction for the progressive tense is **similar** between Spanish and English. In a sentence with a *determiner gender violation*, the gender of a noun phrase was switched to the incorrect gender, resulting in a violation at the following noun. This syntactic construction is **unique** to Spanish compared to English, since the English language does not express grammatical gender. In a sentence with a *determiner number violation*, the number of the determiner was switched to the incorrect number, resulting in a violation at the following noun. In both languages, plurality of a noun is expressed by an inflectional morpheme on the noun. However, unlike English, Spanish also expresses plurality in the determiner preceding the noun, which makes the syntactic construction **different** from English. Tokowicz and MacWhinney (2005) found that the P600 effect was reduced (in fact, it was not statistically significant) for determiner number violations compared to the other two types, which suggests that aspects of L1 syntax affect L2 processing; a phenomenon known as syntactic transfer. Specifically, the fact that number is not expressed on the determiner in English would make native English speakers less sensitive to determiner number in L2 Spanish. The same does not apply to determiner gender because there is no English grammatical gender to transfer to L2 Spanish.

### 5.1.2 Computational models of ERP effects

Although ERPs are useful in psycholinguistic research, their precise functional interpretation is still unclear (Beres, 2017; Kaan, 2007). Several computational cognitive models have been proposed to account for ERPs (for a review see: Eddine, Brothers, & Kuperberg, 2022). Some of these models take the magnitude of change in neural *activation* as a measure of ERPs (Rabovsky, Hansen, & McClelland, 2018) while others take the network's *prediction error* to account for ERP effect size (Brouwer, Crocker, Venhuizen, & Hoeks, 2017; Fitz & Chang, 2019; Frank, Otten, Galli, & Vigliocco, 2015). Only few models provide an interpretation of the P600 (Brouwer et al., 2017; Fitz & Chang, 2019; J. Li & Futrell, 2023).



Specifically, Fitz and Chang (2019) used Chang's (2002) Dual-path model to show that prediction error corresponds to N400 size and backpropagated error corresponds to P600 size across a wide range of studies, providing support for the hypothesis that ERPs might reflect learning signals in the language system. This account of the N400 and P600 is known as the Error Propagation account.

### 5.1.3 The present study

Here, we first investigated whether L2 learning progression reflects on the ERPs in simulated participants like in human participants. We did so by taking a monolingual computational cognitive model of sentence production that had been used to explain ERPs, and extending it to the bilingual case using the Bilingual Dual-path model (Tsoukala, Broersma, et al., 2021). Second, we investigated effects of cross-linguistic similarity on simulated P600s in the model.

#### 5.1.3.1 L2 learning

We first performed a computational modelling experiment to investigate simulated L2 learners progress through syntactic learning, and further tested the viability of Error Propagation as an account of ERPs. We did this by ascertaining whether a P600 effect could be simulated by the Bilingual Dual-path model, and whether the magnitude of this effect increased in later L2 learning. We simulated native speakers of Spanish (L1) who start learning English (L2) at a later age. As L2 learning progressed, we ran a subject-verb number agreement experiment similar to one of the experiments in Fitz and Chang (2019), presenting simulated participants with stimuli containing syntactic violations that elicit a P600 in native speakers (Osterhout et al., 2008; Tanner et al., 2013, 2014), and with control sentences without such violations.



We expected to find a simulated P600 effect in the Bilingual Dual-path model, since Fitz and Chang (2019) were able to have the monolingual Dual-path model reproduce N400 and P600 effects for stimuli used in a number of human EEG studies. We further expected N400 and P600 effects to occur and their magnitude to decrease and increase, respectively, as learning progressed, because ERP effects and their magnitude in L2 learners have been shown to be primarily determined by proficiency (Antonicelli & Rastelli, 2022; Caffarra et al., 2015; McLaughlin et al., 2010; Morgan-Short, 2014). We specifically expected the P600 effect to be more pronounced as later learning progresses further, since advanced L2 learners show native-like ERP waveforms for L2 grammatical features (Morgan-Short, 2014). Additionally, we specifically expected the N400 effect to decrease in magnitude later in the learning process, because lexical learning precedes syntactic learning in L2 learners and L2 learners seem to rely on lexical processing early on because of this (McLaughlin et al., 2010).

### 5.1.3.2 Cross-language similarity

In Section 5.3 we used the Bilingual Dual-Path model to investigate whether the Error Propagation account could explain the P600 results from Tokowicz and MacWhinney (2005). The model simulates native speakers of English (L1) who start learning Spanish (L2) at a later age. At every point in L2 learning, we ran an experiment similar to that of Tokowicz and MacWhinney (2005), presenting simulated participants with sentences containing a verb-tense violation, a determiner gender violation, or a determiner number violation, or with a control sentence without any violation.

Based on findings from human ERP studies (Foucart & Frenck-Mestre, 2011, 2012; McLaughlin et al., 2010; Morgan-Short, 2014), we expected a clear P600 effect of violations expressed similarly in L1 and L2 (i.e, verb-tense violations) and a clear P600 effect to grammaticality violations expressed uniquely in L2 (i.e., determiner gender violations). We expected a reduced P600 effect (in line with Sabourin & Stowe, 2008) or even an absent P600 effect (in line with Tokowicz & MacWhinney, 2005) to the determiner number violations compared to the other two violation types. The results from our simulations were largely in line with these expectations, although they did not clearly confirm our expectations for the determiner gender violations. We therefore conducted a second simulated experiment with simulated monolinguals to further explore this discrepancy. Differences between the monolingual and bilingual model predictions suggest the bilingual model does display syntactic transfer, where L1 syntax affects L2 syntactic processing.



## 5.2 L2 learning (Experiment 1)

### 5.2.1 Method

To simulate late Spanish-English bilinguals, we trained instances of the Bilingual Dual-path model to learn Spanish from the start and English as L2 later on. The training input to the model consisted of sentences from two artificial languages (modelled on Spanish and English) that were paired with messages that encoded their meaning. The model learned to express messages as sentences of the target language (Spanish or English) by predicting the next word.

#### 5.2.1.1 Artificial languages

Table 5.2 shows the different constructions in the artificial languages. Constructions were distributed uniformly in the training input. Taken together, the two artificial languages consisted of 258 lexical items: 121 nouns, 11 adjectives, 6 pronouns, 6 determiners, 12 prepositions, 87 verbs, 7 auxiliary verbs, 6 verb inflectional morphemes, 1 plural noun marker, and the period. The inflectional morphemes were used to generate verbs with simple, progressive and perfect aspect in present or past tense. The plural noun

**Table 5.2:** Constructions and English example sentences. In the artificial language modelled on English, inflectional morphemes -prg, -prf and -ss are used for verb conjugations in progressive, perfect, and 3rd-person present simple tense, respectively.

| Construction | Example sentence |
|---|---|
| Animate intransitive | The woman is play -prg |
| Animate with intransitive | The woman is play -prg with a dog |
| Inanimate intransitive | The apple is fall -prg |
| Locative | The boy is walk -prg around the school |
| Theme-experiencer (active) | The uncle surprise -ss the grandfather |
| Theme-experiencer (passive) | The grandfather is surprise -prf by the uncle |
| Transitive (active) | The girl bake -ss a cake |
| Transitive (passive) | The cake is bake -prf by the girl |
| Cause-motion | The hostess is put -prg a cactus into the office |
| Benefactive transitive | The grandmother repair -ss the cup for the girl |
| State-change | The waiter is fill -prg the cup with water |
| Locative alternation | The man spray -ss the sink with water |



marker was used to generate plural nouns.

The meaning space had 116 concepts and 7 thematic roles. Thematic roles are similar to those from Chang et al. (2006). To provide a simple example, the meaning of "the old lady carves a cake" would be represented as AGENT: LADY; ACTION-LINKING: CARVE; PATIENT: CAKE; AGENT-MODIFIER: OLD. This is implemented by introducing fixed-weight connections between role units and concept units.

#### 5.2.1.2 Model configuration and training

For our simulations, we modified the Bilingual Dual-path model to resemble the architecture used in Fitz and Chang (2019): Previous word-history and role-history layers were added to the model, which kept a running average of the activation of the input layer and role layer, respectively, and were connected to the hidden layer.

As pre-registered[1], all models used 50 hidden-layer units and 30 compress-layer units. Internal layer units used the logistic activation function; the output layer units used a softmax activation function. Weights were initialized randomly, uniformly be-

[1] The pre-registration can be accessed here: https://aspredicted.org/blind.php?x=CGL_X3R

tween $\pm 1$. Fixed weights for concept-to-role connections and realization-to-role connections were set to a value of 6. The concept layer had a set bias of $-3$.

As pre-registered, for each of 60 model subjects and for Spanish and English combined, we generated 10,000 unique message-sentence pairs for training and a novel set of 200 message-sentence pairs for testing. The sentences are approximately equally divided over the two languages, where the percentage of Spanish sentences was sampled from a uniform distribution between 48% and 52% and the rest was English. Following Fitz and Chang (2019), the message was excluded from 70% of the training items. Each model first iterated five times over its monolingual Spanish training set, followed by 75 epochs over its bilingual training set. The training set's order was randomized at the beginning of each of these 80 epochs. The model learned by steepest descent backpropagation, with momentum set to 0.9. Initially, the learning rate was set to 0.1, it decreased linearly to 0.02 over the 5 epochs of monolingual training, and then stayed constant during bilingual training.



#### 5.2.1.3 Model evaluation

After each epoch, model accuracy was tested using a 200-sentence test set. The model's L2 English proficiency was evaluated with two measures. First, syntactic accuracy was measured as the percentage of sentences for which all words had the correct part of speech. Second, meaning accuracy was measured as the percentage of syntactically correct sentences that also conveyed the target message without additions. As pre-registered, we excluded the 20 subjects with the lowest meaning accuracy, leaving data from 40 model subjects.

#### 5.2.1.4 Differences between simulated participants

Weights were initialized randomly, and differed between simulated participants. The percentage of Spanish versus English (training and testing) sentences varied between subjects, ranging from 48/52 to 52/48. The distribution of constructions is the same for all subjects. Training, testing and experimental trial sentences in the same language with the same constructions can differ between subjects in two ways. Firstly, sentences

**Table 5.3:** Example sentences for the experimental trials. The bold morphemes indicate the sentence position where prediction error was measured.

| Example sentence | Subject Nr | Agreement |
|---|---|---|
| the old lady carve **-ss** a cake | Singular | Control |
| the old lady carve **a** cake | Singular | Violation |
| the old lady -s carve **a** cake | Plural | Control |
| the old lady -s carve **-ss** a cake | Plural | Violation |



can differ in content-words resulting in different meaning of sentences. Secondly, singular nouns can differ in definiteness of the article.

#### 5.2.1.5 Experimental trials

To elicit ERPs, we generated 30 English sentence pairs, each consisting of a control and a violation item. The control was an active transitive sentence where the verb form agreed with the subject in number. In the violation item, the verb did not agree with subject number. Violations were created by adding or omitting the inflectional marker for singular verbs (-ss), see Table 5.3.

#### 5.2.1.6 Measuring model ERPs

After every training epoch, the model was tested on the experimental sentence pairs. As in Fitz and Chang (2019), learning was turned on in the model during processing, but connection weights were reset to the weights of the respective training epoch after each test sentence in order to exclude learning effects during the experiment. The state in which the model encountered each trial was thus the same for all of the sentences.

We measured the prediction error at the output layer and the hidden layer (for details see Fitz & Chang, 2019). The prediction error of output unit $j$ is the difference between its activation $y_j$ and the target activation $t_j$, or: $\delta_j = y_j - t_j$, with $y_j \in [0, 1]$ and $t_j \in \{0, 1\}$. This error was backpropagated in the network, as happens during training, to generate error at deeper layers. Error for units connected to the output layer was calculated as shown in Eq. 5.1, where $k$ indexes the units connected to the output layer with weight $w_{kj}$, and $j$ references the units that are backpropagating error.

$$\delta_k = y_k(1 - y_k) \sum_{j=1}^{n} \delta_j w_{kj} \quad y_k \in [0, 1] \tag{5.1}$$

Error was calculated the same for other layers backpropagating error into the network. The error was collected after the transitive verb where the third-person singular morpheme was present or absent. The simulated N400 and P600 sizes are the sums over $|\delta|$ of the output- and hidden-layer units, respectively. Note that the scales of these two measures are not comparable because the output units, unlike the hidden units, use the softmax activation function and therefore their activations always sum to 1.



### 5.2.2 Results

Figure 5.1 displays the simulated participants' proficiency at the start and the end of bilingual training.

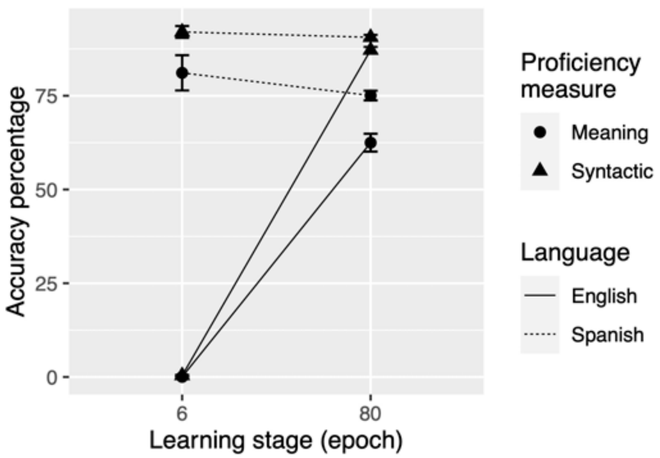


**Figure 5.1:** Mean proficiency of simulated participants. The syntactic and meaning accuracies are displayed for the first and last epoch of bilingual training. The error bars show the 95% confidence interval.

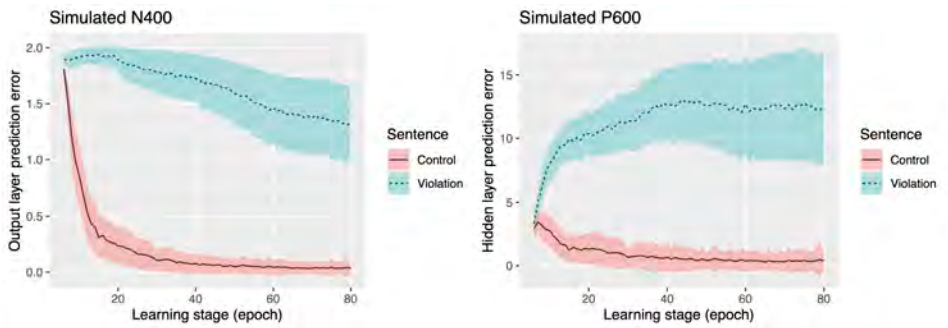




**Figure 5.2:** Mean prediction error (averaged over all model subjects) as a learning progresses, in the output layer (left panel) and in the hidden layer (right panel), for number agreement violation and control items. Shaded areas represent the 95% CI.

The mean prediction error as L2 learning progressed, at the hidden layer and the output layer respectively, are displayed in Figure 5.2. At the output layer, the mean error (simulating N400) for the VIOLATION items, was 1.89 at the start of bilingual training and increased to 1.93 at epoch 19, whereafter it decreased to 1.33 over the learning epochs. The mean error at the hidden layer (simulating P600) for the VIOLATION condition was 3.30 at the start of bilingual training, and increased over the learning epochs to 12.52. For the CONTROL items, error at both layers was high initially, but decreased to values close to 0 during L2 learning.

**Table 5.4:** Summary of the fixed effects in the linear mixed-effects models.

| Predictor | Est. | 95% CI | SE | df | $t$-value | Pr(> $\|t\|$) |
|---|---|---|---|---|---|---|
| Intercept | 3.54 | [3.32, 3.75] | 0.11 | 40.00 | 33.84 | <0.001 |
| agreement | 3.00 | [2.81, 3.20] | 0.10 | 40.05 | 30.76 | <0.001 |
| layer | 2.61 | [2.41, 2.82] | 0.10 | 40.00 | 26.17 | <0.001 |
| learning_progress | 0.10 | [−0.04, 0.24] | 0.07 | 40.17 | 1.41 | 0.165 |
| agreement × layer | 2.28 | [2.10, 2.46] | 0.09 | 40.04 | 25.49 | <0.001 |
| agreement × learning_progress | 0.50 | [0.36, 0.63] | 0.07 | 40.15 | 7.31 | <0.001 |
| layer × learning_progress | 0.31 | [0.19, 0.43] | 0.06 | 40.18 | 5.08 | <0.001 |
| agreement × layer × learning_progress | 0.49 | [0.37, 0.61] | 0.06 | 40.16 | 8.34 | <0.001 |

#### 5.2.2.1 Pre-registered analysis

As pre-registered, we analyzed the data from our experiment with a linear mixed-effects model, using the lmer function from the package lme4 (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2013). The model fits the prediction error from the Bilingual Dual-path model, a numerical value. The regression model[2] included the predictors of interest: AGREEMENT, LAYER, LEARNING_PROGRESS and their interactions. AGREEMENT and LAYER were sum-coded. AGREEMENT levels Control and Violation were coded $-1$ and $+1$, respectively. Levels Hidden and Output of LAYER were coded $+1$ and $-1$, respectively. The number of L2 training epochs is indicated by the LEARNING_PROGRESS predictor, which was standardized. We fit random intercepts for model participants, and by-participant random slopes for the three predictors of interest and their interactions. Table 5.4 reports estimates, 95% confidence intervals, standard errors, degrees of freedom, $t$-values and $p$-values.

The positive estimate for the interaction between the predictors AGREEMENT, LAYER and LEARNING_PROGRESS (Estimate = 0.49, 95% CI = [0.37, 0.61]) indicates that learning progress affects the two layers' sensitivity to violated sentences differently. The estimate has a confidence interval not including zero, thus there was an effect of the three-way interaction between these predictors. As Figure 5.2 clearly shows, this interaction is driven by an increasing effect of violation in the hidden layer combined with a decreasing effect of violation in the output layer.

### 5.2.3 Discussion

We investigated how syntactic processing developed in simulated L2 learners as learning progressed. We used a connectionist model of syntactic development (Chang, 2002) to simulate Spanish-English bilinguals and exposed the model to L2 number-agreement violations at different points in time. Similar to the account in Fitz and Chang (2019), we recorded ERPs in response to these syntactically anomalous sentences from the model. On this account, ERPs are summary signals of brain

[2] The script for the mixed-effects model can be accessed here: `https://osf.io/yprjk/?view_only=aae2b8a52819475eb127721931de19ba`

5

activity that index the propagation of prediction error during comprehension whose functional role is to support learning. Prediction error at the output layer was used to model the N400 and the backpropagated prediction error at the hidden layer was used to model the P600. The results of our simulations revealed a clear P600 effect for syntactically anomalous sentences in the L2, as well as a clear N400 effect early in acquisition. We also found that over time the P600 increased as the model became more proficient in the L2 and the N400 decreased over time. These findings are similar to human L2 learners as reported in several ERP studies on second language acquisition (Antonicelli & Rastelli, 2022; Caffarra et al., 2015; McLaughlin et al., 2010; Morgan-Short, 2014). Thus, our results support a theory of syntactic learning in L2 learners where the magnitude of different ERP components changes during acquisition.



In our simulations, monolingual training resulted in optimal network weights for the L1, after which new L2 learning required a considerable amount of further training. At the beginning of L2 learning, the model does not know the English syntax for noun-verb number agreement. Consequently, after seeing the verb, the model activates a variety of candidate words and morphemes, which leads to large prediction error at the lexical output layer, and thus a large-amplitude N400 prediction. Prediction error at the hidden layer indexing the P600, in contrast, is relatively small because the model has not yet learned the syntax of agreement. As the model gradually acquires agreement, word predictions after the verb become increasingly more accurate because they are more and more driven by learned syntactic knowledge in the hidden layer. When the model is presented with a number agreement violation item, there is now a larger mismatch between the observed violation and the correct word predictions made by the model at this sentence position. Because the correct prediction is due to syntactic knowledge at the hidden layer, the hidden layer gets the majority of the blame when such a mismatch occurs. Thus, the size of the P600 effect increases during syntactic learning. The lexical output layer, on the other hand, gradually receives less blame as the syntax of agreement is acquired deeper in the network, which leads to a decrease in the N400 effect over time.

The error propagation account explains why ERPs elicited by lexical violations (N400) precede ERPs in response to syntactic violations (P600) and this account has been able to reproduce key findings from a considerable number of monolingual ERP studies (Fitz & Chang, 2019). The results presented here on bilingual ERPs, and how they change over development, adds further support for this account. Apart from the error propagation account, the model of Brouwer et al. (2017) can also explain monolingual N400 and P600 effects but it remains to be tested whether this model would be able to simulate ERP effects in bilinguals and the change in size of these effects during second language acquisition. What is unique about the error propagation account is that it can naturally model and explain ERPs in development because on this account ERPs are directly linked to learning. Therefore, the magnitude of ERP effects is expected to change as different pieces of linguistic knowledge are acquired.



## 5.3 Cross-language similarity (Experiment 2a: simulated L2 learners, and Experiment 2b: simulated monolingual controls)

### 5.3.1 Method

In Experiment 2a, we simulated L1 speakers of English who are learning L2 Spanish to investigate whether syntactic (dis)similarities between L1 and L2 affect simulated L2 learners in the same way as human L2 learners. We trained instances of the Bilingual Dual-path model[3], using a similar model configuration as in Experiment 1 to learn English from "infancy" and Spanish as L2 at a later stage. The model configuration in this experiment differs from the configuration in Section 5.2 in how the model's next-word prediction is fed back into the model, forming its input signal at the next time step. Following Fitz and Chang (2019) closely, the input of the current model is set to the single highest activation value of the sum of the output vector (i.e., the distribution over possible next words) and the target vector (representing the single target word). This method emphasizes correct word prediction over actual word prediction, whereas in Section 5.2, the target vector was not part of the input at the next time step. In Experiment 2b we simulated a control group of monolingual speakers of Spanish.

[3]The model code and script for the GAMMs can be accessed here: `https://osf.io/nbxu6/`

**Table 5.5:** Example of an experimental sentence in all for conditions. The bold morphemes indicate the sentence position where the violation occurs.

| Example sentence | Violation condition |
|---|---|
| el padre hacer -a-e una bañera | none (control) |
| el padre hacer **-ger** una bañera | Tense |
| los padre -s hacer **-a-e** una bañera | Number |
| la **padre** hacer -a-e una bañera | Gender |



#### 5.3.1.1 Artificial languages and model training

The artificial languages had the same constructions as the languages created for Experiment 1. The two artificial languages together consisted of 259 lexical items: 121 nouns, 11 adjectives, 6 pronouns, 6 determiners, 12 prepositions, 87 verbs, 8 auxiliary verbs, 6 verb inflectional morphemes, 1 plural noun marker, and the period. Using the inflectional morphemes, verbs were generated in present or past tense, with simple, progressive or perfect aspect. Plural nouns were generated using the plural noun marker. Plural determiners in Spanish were individual words, namely "los" and "las". For example, the semantic message AGENT: ORANGE, PL; ACTION-LINKING: DISAPPEAR; TARGET-LANGUAGE: ES would be expressed in Spanish by the sentence: "las naranja -s desaparecer -an-en".

The training and test sets were generated in the same way as for Experiment 1. Each model instance iterated five times over its monolingual English training set first, before iterating for 45 epochs over its bilingual training set. The training set's order was randomized at the start of each epoch. The model learned by steepest descent backpropagation, which was configured in the same way as for Experiment 1. The simulated monolinguals were trained in the same way as the simulated L2 learners, except that all the message-sentence pairs were in Spanish.

#### 5.3.1.2 Differences between simulated participants and evaluation

Differences between simulated participants were achieved in the same way as for Experiment 1, and their linguistic proficiency was also measured in the same way. As pre-registered[4], we only included the 40 simulated participants with the highest meaning accuracy in our analysis.

#### 5.3.1.3 Experimental trials

We generated 30 Spanish control sentences to obtain simulated ERPs for. For each of the control sentences we constructed a version for every violation type used by Tokowicz and MacWhinney (2005) (see Table 5.5). The control sentence was a syntactically correct, active transitive sentence. There were three violation types: (1) Tense violations, where the inflectional marker for singular verbs (-a-e) was changed to progressive verbs (-ger). (2) Determiner number violation, where the singular determiner was changed to a plural determiner. (3) Determiner gender violation, where the determiner's grammatical gender was changed. These three violations involve features that are similar to English, different from English, or unique to Spanish, respectively.



#### 5.3.1.4 Measuring simulated P600s

The simulated participants were tested on the experimental sentences after every training epoch. Following Experiment 1, learning was turned on in the model while processing the experimental and control sentences, but connection weights were reset to the weights of the respective training epoch after each of those sentences to prevent learning effects during the experiment. Therefore, the simulated participants encountered each trial in the same state for all of the sentences.

As we did in Experiment 1, we measured prediction error at the hidden layer (see Fitz & Chang, 2019, for details). The prediction error of output unit $j$ is the difference between its activation $y_j$ and the target activation $t_j$, or: $\delta_j = y_j - t_j$, with $y_j \in [0,1]$ and $t_j \in \{0,1\}$. In the same way as during training, error backpropagated through the network to generate error at deeper layers. Error for units connected to the output layer was calculated as shown in Eq. 5.1, where $k$ indexes the units connected to the output layer with weight $w_{kj}$, and $j$ references the units that are backpropagating error.

[4]The pre-registration can be found here: `https://aspredicted.org/HSR_NKN`

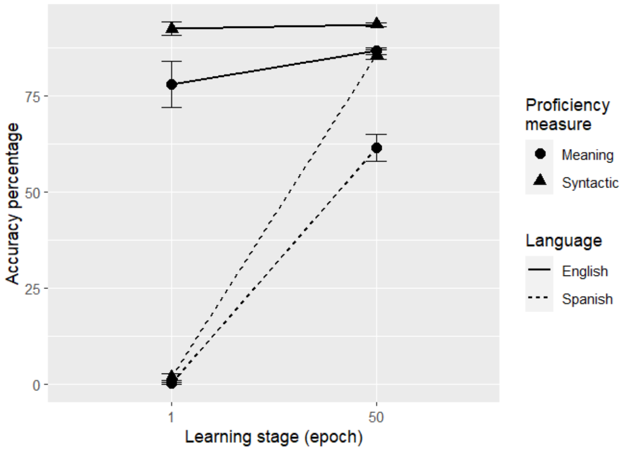


**Figure 5.3:** Mean proficiency of the simulated L2 learners. The syntactic and meaning accuracy are displayed for the first and last epoch of bilingual training. The error bars show the 95% confidence interval.

Error was also calculated this way for other layers backpropagating error through the network. The simulated P600 sizes are the sums over $|\delta|$ of the recurrent-layer units. The error resulting from a violation was collected at the first position where the sentence becomes ungrammatical (see Table 5.5). These errors were compared to errors at the same position of control sentences.

### 5.3.2 Results

#### 5.3.2.1 Experiment 2a: simulated L2 learners

Figure 5.3 displays the proficiency of the simulated L2 learners at the start and the end of bilingual training. The model learns both languages to a high degree, although (unsurprisingly) it remains more proficient in L1 English than L2 Spanish.

The mean backpropagated error at the hidden layer as L2 learning progresses is displayed in Figure 5.4. As pre-registered, we analyzed the data from our experiment with two generalized additive mixed-effects models (GAMMs; Hastie, 2017), using the bam

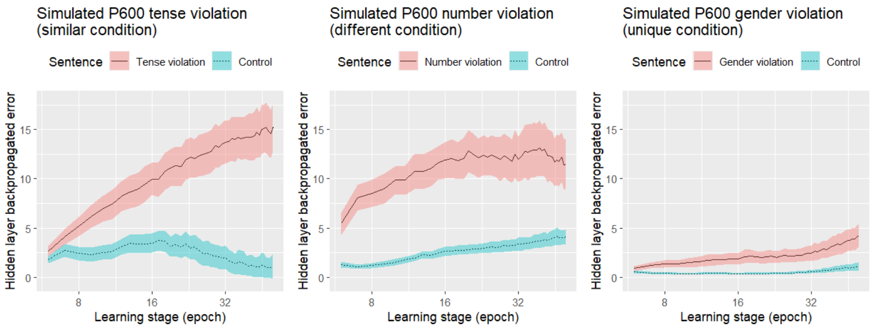




**Figure 5.4:** Mean backpropagated error (averaged over all bilingual trained simulated learners) as a function of learning progress in the hidden layer, split between the three violation types. Learning progress is log-scaled. Shaded areas represent the 95% CI.

function from the package mgcv (Wood & Wood, 2015) in R (R Core Team, 2018b). Both GAMMs fit the simulated P600 effect, that is, the difference between violation and control sentences in the backpropagated error in the Bilingual Dual-path model. We fit a GAMM to determine if P600 effects differ between violation conditions Similar and Different (i.e., tense and number violations), and we fit a second GAMM to determine if P600 effects differ between conditions Unique and Different (i.e., gender and number violations).

The first GAMM[3] included the predictors of interest: DIFFERENT, LEARNING_PROGRESS, and their interaction. DIFFERENT indicated violation type and was dummy-coded with levels Similar and Different, coded as $0$ and $1$ respectively. LEARNING_PROGRESS is the number of L2 training epochs (standardized). We included by-participant random slopes for DIFFERENT and by-participant random smooths for LEARNING_PROGRESS. See Table 5.6 (left-hand side) for a summary of the fitted GAMM. We clearly see predicted P600 effects in the Similar and Different conditions, but it is reduced in the Different compared to the Similar condition, in line with our expectations. The simulated P600 effect grows significantly over LEARNING_PROGRESS ($F = 33.60$, edf = 8.61, $p < .001$) and this growth differs between the violation types ($F = 2202.45$, edf = 8.39, $p < .001$).

**Table 5.6:** Summary of the components in the generalized additive mixed-effects models fit on data from bilingual participants, comparing violation conditions Similar and Different (left; predictor Different: Similar = 0, Different = 1) and the conditions Unique and Different (right; predictor Different: Unique = 0 and Different = 1).

| Similar vs. Different | | | | |
|---|---|---|---|---|
| Predictor (coefficient) | Est. | SE | $t$-value | Pr($>\|t\|$) |
| (Intercept) | 9.12 | 0.27 | 33.30 | $<$0.001 |
| Different | 0.70 | 0.39 | 1.81 | 0.07 |
| Predictor (smooth) | edf | Ref.df | $F$-value | Pr($>\|t\|$) |
| s(Learning_progress) | 8.61 | 8.72 | 33.60 | $<$0.001 |
| s(Learning_progress:Different) | 8.39 | 8.89 | 2202.45 | $<$0.001 |
| s(Learning_progress, participant) | 295.03 | 359.00 | 48.34 | $<$0.001 |
| s(Different, participant) | 77.83 | 78.00 | 447.96 | $<$0.001 |

| Unique vs. Different | | | | |
|---|---|---|---|---|
| Predictor (coefficient) | Est. | SE | $t$-value | Pr($>\|t\|$) |
| (Intercept) | 5.26 | 0.27 | 20.83 | $<$0.001 |
| Different | 4.76 | 0.31 | 15.27 | $<$0.001 |
| Predictor (smooth) | edf | Ref.df | $F$-value | Pr($>\|t\|$) |
| s(Learning_progress) | 7.44 | 7.78 | 8.94 | $<$0.001 |
| s(Learning_progress:Different) | 8.79 | 8.98 | 334.19 | $<$0.001 |
| s(Learning_progress, participant) | 307.02 | 359.00 | 2748.53 | 0.05 |
| s(Different, participant) | 68.57 | 78.00 | 283.45 | $<$0.001 |

The second GAMM[3] is the same as the first model, except for one predictor of interest, namely DIFFERENT which in this case had the levels Unique and Different, coded as 0 and 1, to determine if models respond differently between violation conditions Unique (i.e., gender violation) and Different (i.e., number violation). See Table 5.6 (right-hand side) for a summary of the fitted GAMM. We see a weak simulated P600 effect in the Unique condition, which is smaller than the P600 effect in the Different condition. This is not in line with our expectations. The simulated P600 grows significantly over LEARNING_PROGRESS ($F = 8.94$, edf = 7.44, $p < .001$) and this growth differs between the violation types ($F = 334.19$, edf = 8.79, $p < .001$).

### 5.3.2.2 Experiment 2b: simulated monolingual controls

Mean Spanish meaning accuracy and mean Spanish syntactic accuracy were 99.98% and 99.99%, respectively, at the end of training.

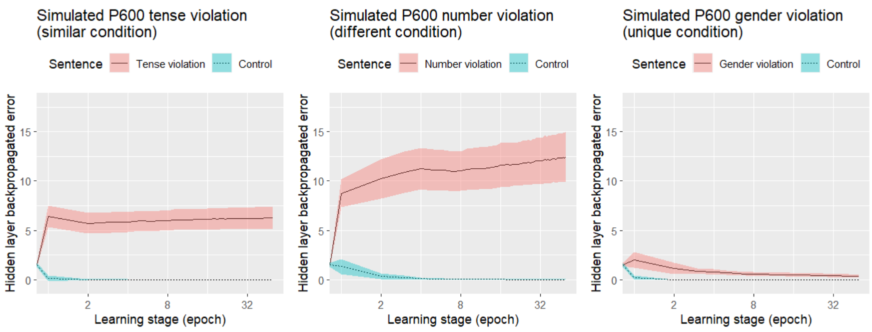


**Figure 5.5:** Mean backpropagated error (averaged over all monolingual trained model subjects) as learning progresses in the hidden layer, split between the three violation types. Learning progress is log-scaled. Shaded areas represent the 95% CI computed over items.

The mean backpropagated error at the hidden layer as learning progresses is displayed in Figure 5.5.

Similar to our pre-registered analysis, we analyzed the data from our experiment with two GAMMs, to determine if participants respond differently between conditions Similar and Different, and between Unique and Different. Both GAMMs fit the simulated P600 effect from the Bilingual Dual-path model, here trained only on Spanish input. For the GAMM comparing Similar and Different violations, there is a larger simulated P600 effect for the Different condition compared to the Similar condition. This P600 effect significantly grows over LEARNING_PROGRESS ($F = 1141.37$, edf $= 8.61, p < .001$) and this growth differs between the violation types ($F = 488.73$, edf $= 8.39, p < .001$). For the GAMM comparing Unique and Different violations, there is a larger simulated P600 effect in the Different condition compared to the Unique condition. In fact, the simulated P600 effect in the Unique condition is very small. The simulated P600 effect over LEARNING_PROGRESS

($F = 301.10, \text{edf} = 7.44, p < .001$) and this growth differs between the violation types ($F = 1864.80, \text{edf} = 8.79, p < .001$).

### 5.3.3 Discussion



Experiment 2 investigated whether syntactic (dis)similarities between L1 and L2 affect simulated L2 learners in the same way as human L2 learners. We simulated English-Spanish bilinguals and, throughout L2 learning, exposed them to three types of syntactic L2 violations that differ in their relation to the L1. We recorded simulated P600s in response to these syntactically anomalous sentences by calculating propagated prediction error at the hidden layer, following the Error Propagation account in Fitz and Chang (2019). On this account, ERPs are summary signals of brain activity that index the propagation of prediction error during comprehension whose functional role is to support learning.

The results of our bilingual simulations are only partially in alignment with our expectations. As expected, our results reveal stronger P600 effects when syntactically anomalous sentences in the L2 contain a tense violation (similar between English and Spanish) compared to a number violation (different between English and Spanish). However, the simulated P600 effect when the L2 sentences contain a gender violation (unique to Spanish) was very weak, especially compared to the other two types of syntactic violations, in contrast with our expectations.

We simulated a monolingual control group and found that it predicts a *larger* P600 effect in the number violation condition compared to the tense violation condition. This is the opposite from what was found for the bilingual model's L2 and therefore support the idea that properties from the L1 affect processing in the L2 (i.e., syntactic transfer) in our model, as also appears to happen in humans (De Garavito & White, 2002; Ionin, Zubizarreta, & Philippov, 2009; Montrul, 2010; White, Valenzuela, Kozlowska-Macgregor, & Leung, 2004).

Moreover, compared to the bilingual model, the monolingual model showed an even smaller P600 effect in the gender violation condition; an effect that reduced over L1 training whereas it increased over L2 training. Thus, it appears there is also syntactic transfer from L1 to L2 going on in the processing of gender violations.

It is not entirely clear why backpropagated error is low in response to a gender violation but not in response to a number violation. A possible explanation is the implementation of syntactic features in the model. The messages that accompany sentences during training encode tense as well as plurality of nouns, but not gender. Grammatical gender is present and expressed in our artificial language of Spanish, but there is no representation of gender in the concept layer of the model. Specifically, there is no gender node in the concept layer preceding the hidden layer, to backpropagate error to. Furthermore, verb conjugation indicating tense, as well as plurality of nouns, are expressed by morphemes that follow verbs or nouns, respectively. The model treats these morphemes as words. We have no such morphemes for gender, only separate gendered determiners for Spanish.



## 5.4 Conclusion

The error propagation account explained key findings from a considerable number of monolingual ERP studies (Fitz & Chang, 2019). Experiment 1 simulated bilingual N400s and P600s and how they change during development, adding further support to this account. In Experiment 2a, the reduced P600 for number violation compared to tense violation supports a theory of syntactic transfer affecting ERP effects in L2 learners. The model in its present state, however, was unable to produce a strong P600 in response to a grammatical gender violation, in contrast with human participants (Antonicelli & Rastelli, 2022; Caffarra et al., 2015; McLaughlin et al., 2010; Foucart & Frenck-Mestre, 2011; Frenck-Mestre, Foucart, Carrasco-Ortiz, & Herschensohn, 2009; Morgan-Short, 2014; Tokowicz & MacWhinney, 2005). Further work is needed to determine if the Error Propagation account, as implemented in the Bilingual Dual-path model, simulates a strong P600 effect in response to a grammatical gender violation when gender is implemented in the message in the same way as plurality and tense. A limitation of the current model is that it does not account for differences in the precise onset of the N400 or P600 and that it does not model earlier ERP components such as the early left-anterior negativity (eLAN) which has been elicited in some bilingual studies (Caffarra et al., 2015).

# 6

# Mixing while matching in bilingual sentence production: Code-switching increases cross-language structural priming

## Abstract

Studies on cross-language structural priming and on code-switching suggest that syntax is shared between languages in a bilingual's language system. However, it is not clear if and how these bilingual language phenomena might interact.

Assuming an implicit learning account, we tested whether code-switching in the prime sentence increases syntactic implicit learning, leading to stronger cross-language structural priming. We first conducted four simulated Spanish-to-English structural priming experiments using the Bilingual Dual-path model (Tsoukala, Broersma, et al., 2021). The Spanish prime sentences had an English (code-switched) determiner and noun, or only a code-switched noun, either at the beginning or end of the sentence, or were entirely in Spanish. Mixed effects analyses revealed a significant positive interaction between code-switch condition and priming, indicating stronger priming, with a code-switched English noun phrase at the very beginning of the sentence, but non-significant interactions otherwise.

In a follow-up study with Spanish-English bilinguals from the US, using that type of code-switch (a determiner and noun at the beginning of the sentence) revealed in increased cross-language structural priming in human participants too.

Together, these results suggest that increased processing incurred by code-switched prime sentences is related to increased prediction error and subsequent implicit learning involving shared syntactic representations. This then leads to an increased cross-language structural priming effect.

## 6.1 Introduction

When bilinguals hear a certain syntactic structure in one language, they often match that structure when producing a sentence themselves in their other language (Hartsuiker et al., 2004; Van Gompel & Arai, 2018). This phenomenon is known as cross-language structural priming. It has been argued, however, that the way bilinguals mix their languages often does not follow the script of typical cross-language priming experiments (Kootstra & Rossi, 2017). They not only switch languages between sentences but also within sentences (i.e., they code-switch). Both code-switching and cross-language structural priming are commonly interpreted as evidence that syntactic knowledge of two different languages is in some way shared in the language system of bilinguals (Hartsuiker et al., 2004; Kootstra et al., 2010; Goldrick, Putnam, & Schwarz, 2016).



In the same way that prime sentences can affect the choice between alternative syntactic structures, experimental (Kootstra et al., 2010; Kootstra, Van Hell, & Dijkstra, 2012; Kootstra, Dijkstra, & Van Hell, 2020) and corpus studies (Fricke & Kootstra, 2016) have revealed that whether and where in a sentence bilinguals produce code-switches is influenced by previous sentences with code-switches that a bilingual has encountered.

Previous research has shown that comprehension of code-switched sentences can incur increased processing costs (see Section 6.1.1). We test whether intra-sentential code-switching increases processing of shared syntactic representations in a way that leads to a stronger structural priming effect compared to cross-language structural priming without code-switching in the prime sentence. We first test this under an implicit learning account of cross-language structural priming as instantiated in the Dual-path model (Chang et al., 2006) and the Bilingual Dual-path model (Janciauskas & Chang, 2018; Tsoukala et al., 2017; Tsoukala, Broersma, et al., 2021). We then test whether this interaction between code-switching and cross-language structural priming also occurs in humans.

### 6.1.1 Processing code-switched sentences

We are interested in what happens during comprehension of prime sentences with code-switches, not in whether code-switches are produced during production of target sentences. Here, we therefore give a short overview of findings on *comprehension* of code-switched sentences. Research on code-switches in sentence comprehension has generally focused on the increased processing costs that code-switches can incur. Studies investigating this have used behavioral as well as electrophysiological methods (for reviews see: Van Hell & Ting, 2015; Van Hell, Fernandez, Kootstra, Litcofsky, & Ting, 2018). In behavioral studies, increased processing is reflected by longer reading times (e.g., Bultena, Dijkstra, & Van Hell, 2015). In electrophysiological research, different ERP components have been associated with processing code-switched sentences, depending on a range of factors, including the code-switch's sentence position and direction. These ERPs include the N400, a negative ERP component that is generally interpreted as a response to a lexico-semantic violation or anomaly (Kutas & Hillyard, 1980), the Left Anterior Negativity (LAN) that has been related to morpho-syntactic processing or working memory (Coulson, King, & Kutas, 1998) and the Late Positive Component (LPC), which is commonly associated with sentence-level processing involving restructuring or reanalysis (e.g., Friederici, 1995; Kaan, Harris, Gibson, & Holcomb, 2000; Tanner, Grey, & van Hell, 2017). This component is generally referred to as the P600 when it is interpreted as a response to a syntactic violation (Hagoort et al., 1993; Osterhout & Mobley, 1995).

Overall, there is ample evidence that code-switching incurs increased processing, which in some cases takes place at the sentence level and might be syntactic in nature. LPCs that could indicate syntactic or other sentence-level processing have been reported in sentence reading studies for code-switches in single sentences (e.g., Moreno, Federmeier, & Kutas, 2002; Van Der Meij, Cuetos, Carreiras, & Barber, 2011) as well as in short stories (Ng, Gonzalez, & Wicha, 2014) and in studies with auditorily presented code-switched sentences (e.g., Fernandez, Litcofsky, & Van Hell, 2019).

Recently, the focus of research on processing code-switches has shifted to how code-switches can affect prediction in language comprehension. A visual world study conducted by Tomić and Valdés Kroff (2022) showed that bilinguals use code-switches to predict a less frequent word in upcoming speech. One interpretation of these results that the authors propose links production and comprehension of code-switches. Code-switching might initially have been a strategy that facilitates production of infrequent words. This could have led to code-switches and those infrequent words co-occurring. Statistical learning could then have resulted in prediction in language comprehension based on those co-occurrences. This idea is an integral part of the Adaptive Predictability hypothesis by Valdés Kroff and Dussias (2023). This hypothesis proposes that bilinguals adapt how they process and predict upcoming bilingual language, including code-switches, based on their experience with such bilingual language, including code-switches. The hypothesis further proposes that cognitive control is the mechanism that drives integration of the two languages in bilingual language comprehension.



### 6.1.2 Cross-language structural priming

Structural priming refers to people's tendency to reuse recently encountered syntactic structures. This tendency occurs in real-life dialogue and is widely considered to be a phenomenon that can provide insight into how syntax is represented in the human mind (Branigan & Pickering, 2017). Structural priming occurs not only within a single language but also between different languages. For example, in a study on priming of transitives, Spanish-English bilinguals produced more *passive* English target sentences (e.g., "*The bottle is hit by the bullet*") after hearing a *passive* Spanish sentence (e.g., "*El camión es perseguido por el taxi*") than after hearing an *active* Spanish sentence (e.g., "*El taxi persigue el camión*") (Hartsuiker et al., 2004). This demonstrates that syntactic representations can be shared between languages. Cross-language structural priming has been investigated in a range of language pairs (for an overview, see Van Gompel & Arai, 2018) including relatively similar languages such as English and Spanish, but also in languages from different families such as English and Korean (Shin & Christianson, 2009). Priming between different languages has been demonstrated for a range of syntactic structures including transitives, genitives (e.g., Bernolet et al., 2013) and datives (e.g., Loebell & Bock, 2003). It occurs in adults as well as in children (Vasilyeva et al., 2010).

Two different mechanisms have been proposed to account for structural priming. The first account explains it as resulting from residual activation of syntactic representations and combinatorial nodes (Pickering & Branigan, 1998). The second account explains it as the result of error-driven implicit learning during processing of the prime sentence (Chang et al., 2006, 2000). Under this account, prediction error can lead to strengthening of connections between representations that support the use of the syntactic structure of the prime sentence. In turn, this implicit learning process leads to increased production of that structure, which is measurable as a priming effect in behavioral experiments. This account has been instantiated in a cognitive neural network model of sentence production, the Dual-path model (Chang et al., 2006).



### 6.1.3 The Bilingual Dual-path model

The Dual-path model is an implicit learning model of sentence production. The first pathway in the model, the sequencing system, is based on the Simple Recurrent Network (SRN; Elman, 1990). This pathway learns how to order words in a sentence. At the same time, the second pathway learns meaning-to-word-form mappings. The model has been used to simulate monolingual structural priming in English (Chang et al., 2006) as well as German (Chang et al., 2015). These studies have shown that structural priming can occur in the model. In doing so they provide support for the implicit learning account of structural priming that the model instantiates. In addition, the model has been used to account for experimental data from various language acquisition studies (e.g., Twomey et al., 2013). Finally, Fitz and Chang (2019) implemented a version of the Dual-path model to simulate results from a range of electrophysiological experiments that investigated N400 effects in response to semantic violations and P600 effects in response to syntactic violations. They propose that such ERP effects can be interpreted as reflecting increased processing related to implicit learning based on prediction error in response to those violations.

Bilingual versions of the Dual-path model have been implemented independently by Tsoukala et al. (2017) and Janciauskas and Chang (2018) to account for experimental data from a number of studies on L2 production and acquisition. See Chapter 2 for an overview of the work that has been done with the Bilingual Dual-path model. In the next section we briefly present such work on code-swtiching and structural priming.

#### 6.1.3.1 Code-switching in the Bilingual Dual-path model

Importantly for the present work, Tsoukala, Broersma, et al. (2021) have shown that the Bilingual Dual-path model can produce human-like code-switches (e.g., "the short boy shows a *libro a un hermano*."), even if the model's training input does not include any code-switched sentences. Furthermore, Tsoukala, Frank, et al. (2021) found that the model's code-switching followed a particular pattern that has been observed among Spanish-English bilinguals: code-switches occur more frequently after the Spanish auxiliary verb "*estar*" ("*to be*") than after the auxiliary "*haber*" ("*to have*"); a phenomenon called the auxiliary phrase asymmetry.



Since the model can produce code-switches and its sentence production mechanism is the same as the mechanism processing input sentences (Dell & Chang, 2014), we expect that the model will also process code-switched input sentences in a human-like way.

#### 6.1.3.2 Cross-language structural priming in the Bilingual Dual-path model

A number of studies have simulated cross-language structural priming in the Bilingual Dual-path model and thereby support implicit learning as the mechanism underlying this phenomenon. In Chapter 3 we conducted simulated experiments with Spanish-English, Dutch-English, and Indonesian-Dutch versions of the model that revealed clear cross-language priming effects.

The results of a Dutch-English model with verb-final Dutch passives and verb-medial English passives show that cross-language priming can occur in the model between (transitive) structures with different word order, in line with results from several behavioural experiments (Bernolet et al., 2009; Chen et al., 2013; Fleischer et al., 2012; Shin & Christianson, 2009). Crucially, this distinguishes the error-driven implicit learning account of structural priming from the hybrid account proposed by Reitter et al. (2011), which predicts that cross-language priming is only possible for structures with the same word order.

All these simulated experiments provide support for a difference between cross-language and within-language priming, with within-language priming being stronger. This is in line with results from behavioural experiments, where within-language priming is also generally stronger, but not always significantly so (e.g., Bernolet et al., 2013).

### 6.1.4 The present work



As discussed in Section 6.1.1, code-switching can incur increased sentence-level processing, which might be syntactic in nature. This increased syntactic processing could reflect implicit learning based on increased prediction error. Since increased error-based implicit learning is what drives cross-language structural priming, the increased sentence-level processing might result in increased cross-language structural priming.

To investigate this, we performed simulated experiments using the Bilingual Dual-path model that was implemented by Tsoukala, Broersma, et al. (2021). As discussed above, this model was used to demonstrate that human-like code-switches can be produced by an implicit learning model even when it was not trained on code-switched input, and it has been shown that the model can simulate cross-language structural priming (see Chapter 3). In our simulations we followed the experimental paradigm from that latter study. We trained model instances on artificial versions of Spanish and English, and then used these models as participants in simulated cross-language priming experiments. In these simulated experiments, we tested whether transitive prime sentences with different types of code-switches can lead to an increased cross-language structural priming effect compared to primes without code-switching.

Based on the results of our simulated experiments, we subsequently tested whether a code-switch to English in the Spanish prime sentence increased the strength of cross-language priming of transitives (from Spanish to English) in human Spanish-English bilinguals.

## 6.2 Simulated experiments

We used the Bilingual Dual-path model (Tsoukala, Broersma, et al., 2021) to conduct four separate simulated experiments to test for a modulating effect of four different code switches on cross-language structural priming from Spanish to English. The code-switches consisted of a single noun either at the beginning or the end of the sentence, or of a noun phrase at the beginning or the end of the sentence. Table 6.1 gives examples of each of these code-switches.

**Table 6.1:** Active prime sentence examples, with two types of code-switches: consisting of a noun only (NOUN) or a determiner and a noun (DET + NOUN), located (Loc.) at the START or END of the sentence, or no code-switch (NONE) with the simulated experiment (Exp.) in which they were used.

6

| Sentence | Type | Loc. | Exp. |
|---|---|---|---|
| (a) ***the boy*** empuja el juguete | DET + NOUN | START | 1 |
| (b) el niño empuja ***the toy*** | DET + NOUN | END | 2 |
| (c) el ***boy*** empuja el juguete | NOUN | START | 3 |
| (d) el niño empuja el ***toy*** | NOUN | END | 4 |
| (e) el niño empuja el juguete | NONE | | all |

### 6.2.1 Method

#### 6.2.1.1 Artificial languages

We used the sentence structures that were used by Tsoukala, Broersma, et al. (2021), to which we added passive transitives. To the lexicon used in that study we added the English preposition “by” and the Spanish preposition “por”. As was the case for the simulations in Chapter 4, 75% of the transitives in our artificial languages were actives while 25% were passives.

#### 6.2.1.2 Training and testing model accuracy

A set of 2,600 unique message-sentence pairs was generated for each simulated participant, 2,000 of which were used for training, while 600 were set aside to test the accuracy of the model. None of these sentences contained code-switches. Following the training procedure in Chapter 3, the message was excluded from 25% of training pairs. The models iterated over their training sets 26 times. After each of these 26 epochs, the model was tested using the test set. The training set was shuffled at the beginning of each epoch.



#### 6.2.1.3 Model configuration

The models had an average number of hidden layer units that was sampled from a uniform distribution between 78 and 82 and an average number of compress layer units sampled from a uniform distribution between 59 and 63. The average fixed weight value for concept role connections was 15, varying from 13 to 17. To simulate English dominant bilinguals, we trained the models with a percentage of sentences in Spanish, the non-dominant language, sampled from a truncated normal distribution (lower bound: 25%, upper bound: 50%) with a mean of 40%, and a standard deviation of 10, while the rest was in English. Other than this, we used the model's default settings.

#### 6.2.1.4 Simulated participants

We trained 120 instances of the model and used these as simulated participants in our simulated experiments. The mean semantic accuracy score for these simulated participants was 71.83% and varied from 31.2% to 91.4%. Their mean percentage of grammatically correct sentences was 98.47% and varied from 91.8% to 100%.

#### 6.2.1.5 Simulated cross-language priming experiments

Independent of the training and test sets, a single set of 50 experimental trials was generated that was used to perform the priming experiment on all of the simulated participants. The priming experiments were conducted in the same way as in Chapter 3, except that neither of the language nodes was activated during processing of the prime sentence. This was done to simulate the code-switched context of the experiment. For the priming experiment, the learning rate was set to 0.06. We used the defaults for other model parameters.

### 6.2.2 Results



In line with earlier results (see Section 6.1.3.2), we found significant cross-language structural priming effects in all four simulated experiments. However, we only found the hypothesized increased priming effect after code-switched primes compared to fully Spanish primes, indicated by a positive interaction between PRIME STRUCTURE and CODE-SWITCHED condition, when the code-switch in the prime sentence consisted of a determiner and noun at the beginning of the sentence (Experiment 1). The other three simulated experiments (Experiments 2, 3, and 4) revealed non-significant negative estimates for that interaction. Here, we report the quantitative results for Experiment 1.

We analyzed only responses that correctly conveyed the target message, while ignoring errors involving the definiteness of articles and missing periods. Based on these exclusion rules, we analysed 71% of the responses on code-switched trials from Experiment 1, as well as 71% of responses on non-code-switched trials.

On trials with code-switched primes, 26.2% of produced sentences were passives after a passive prime, while 21.1% of sentences were passive after an active prime. On trials with non-code-switched primes, 23.1% of sentences were passives after a passive prime, while 19.7% of sentences were passive after an active prime. Figure 6.1 visualizes the priming effects in the two conditions, with a slightly stronger effect on code-switched trials.

#### 6.2.2.1 Analysis

We analysed the results of the simulated experiment by fitting logistic mixed effects models, using a logit link function as implemented in MixedModels.jl (Bates et al., 2013, version 4.28.0) in Julia (Bezanson et al., 2017, version 1.8.0). The model predicts a binary

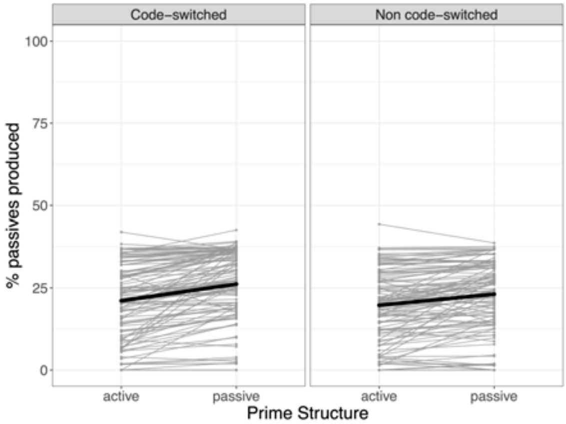


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**Figure 6.1:** Results of Simulated Experiment 1, with code-switched determiner and noun at beginning of prime sentence. Percentage of responses that had a passive structure after either an active prime (21.1%) or a passive prime (26.2%), for code-switched trials (on the left), and percentage of responses that had a passive structure after either an active prime (19.7%) or a passive prime (23.1%) for non-code-switched trials (on the right). The thick black lines visualize the priming effect across all analyzed trials by connecting the percentage of passives responses after active primes to the percentage of passive responses after passive primes. The thin grey lines show the same for each individual simulated participant.

dependent variable, IsPassive, that indicates whether the model produced a passive (1) or active (0) sentence. In addition to the predictors of interest, Code-switched (No = $-0.5$, Yes = 0.5) and PrimeStructure (Active = $-0.5$, Passive = 0.5) and their interaction, the model includes one other contrast-coded predictor: Target-messageBias (Active = $-0.5$, Passive = 0.5). We fit random intercepts for items and simulated participants, and by-participant random slopes for Code-switched, PrimeStructure, and their interaction, as well as correlations between random effects.

As expected based on previous work, the analysis shows a significant effect of Prime Structure (Est. = 0.53 (95% CI: [0.43, 0.62]), $p \leq 0.001$) on the production of passives, indicating a Spanish-to-English cross-language priming effect. The analysis revealed a significant positive interaction between code-switch condition and priming (Est. = 0.18 (95% CI: [0.12, 0.24]), $p \leq 0.001$), showing that priming from Spanish to English in the model is stronger with a code-switched English noun phrase at the very beginning

**Table 6.2:** Fixed effects summary for the logistic mixed-effects model ($N = 33,982$): estimates with 95% confidence intervals and $p$-values for each predictor.

| Predictor | Est. | 95% CI | $p$-value |
|---|---|---|---|
| INTERCEPT | −7.21 | [ −8.9, −5.52] | < 0.001 |
| PRIMESTRUCTURE | 0.53 | [0.43, 0.62] | < 0.001 |
| CODE-SWITCHED | 0.30 | [0.22, 0.39] | < 0.001 |
| TARGET-MESSAGEBIAS | 7.13 | [5.61, 8.65] | < 0.001 |
| CODE-SWITCHED × PRIMESTRUCT. | 0.18 | [0.12, 0.24] | < 0.001 |

of the prime sentence compared to fully Spanish prime sentences.

### 6.2.3 Discussion



With a code-switched determiner and noun at the beginning of the prime (Experiment 1), the model showed increased structural priming compared to entirely Spanish primes, whereas code-switching seemed to lead to slightly weaker priming in the other simulated experiments.

How can the positive interaction between code-switch condition and prime structure be explained? Simulations conducted in Chapter 3 have revealed that within-language priming is stronger than cross-language priming. This might suggest that increased priming due to a code switch to the target language in prime sentences is simply a case of making the cross-language priming in our simulations more like within-language priming. If this was the case, however, we should have seen the same modulating effects for a code-switched noun phrase at the end of the prime sentence as for such a code-switch at the beginning. We therefore conclude that a straightforward interpretation of the code-switched noun phrase making the structural priming effect more like within-language priming is not supported by our simulation results.

Alternatively, the occurrence of a modulating effect of code-switching on priming in only one of the four experiments might be explained by two distinctions between the four code-switches. Firstly, code-switches of a single noun might trigger lexical but not syntactic learning when the model processes the prime. Secondly, prediction of the structure of a sentence is likely to be concluded before a code-switched noun phrase is encountered at the end of a prime sentence, after having processed the verb. For example, when we compare the code-switched prime sentences: "*the swimmer* es golpear -prf por la bruja" and "el nadador es golpear -prf por *the witch*", learning based on prediction of the sentence structure occurs after the first noun phrase. Here, the model will likely predict some verb type that indicates that the sentence is a transitive sentence with an active or passive structure, or some other type of sentence. If the code-switch occurs at this sentence position, increased prediction error because of that code-switch could incur increased learning in the model based on prediction of the sentences structure. In contrast, such learning would be unlikely after the verb phrase, when the sentence structure is already clear.



## 6.3 Behavioral experiment

In this experiment, we tested whether a code-switch to English in the Spanish prime sentence increases cross-language priming of transitives (from Spanish to English) in Spanish-English bilinguals. Based on the results of our simulated experiment, we restricted code-switches to switches involving an otherwise Spanish sentence with an English noun phrase consisting of a determiner and noun at the beginning of the sentence.

### 6.3.1 Method

#### 6.3.1.1 Experimental trials and fillers

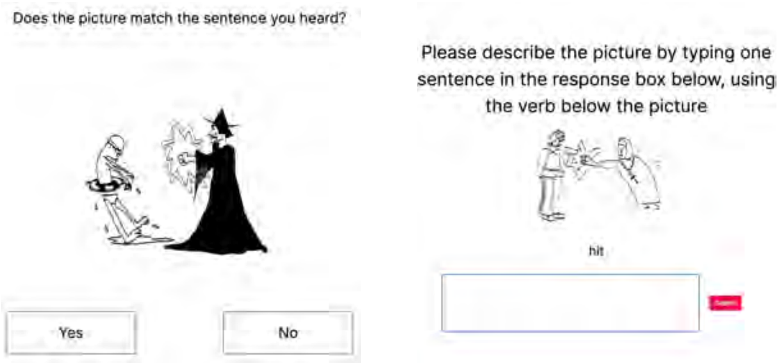
EXPERIMENTAL TRIALS Each experimental trial consisted of a combination of a unique spoken prime sentence and a matching picture (See Figure 6.2a) and a unique target picture (See Figure 6.2b). The prime and target pictures depicted the same transitive action but had no overlap in agent or patient. All transitive events had an agent and patient that were either both people, both animals or both vehicles. The type of agent and patient in the prime sentence and picture were always the same as in the target picture. We used pictures from previous studies on structural priming (e.g., Hartsuiker et al., 2004; Kootstra et al., 2010) and picture databases for psycholinguistic research (Szekely et al., 2004) or constructed new pictures based on those pictures. Prime sentences were recorded by a female early bilingual Spanish-English speaker who was an undergraduate student at the University of Florida. We instructed her to read the stimuli as clearly and naturally as possible. The prime sentences for the trials were either fully in Spanish or were in Spanish with a code-switched English noun phrase at the beginning of the sentence. The verb under the target picture was always in English. We had equal numbers of trials with active and passive primes and equal numbers of trials with a prime sentence that was either a non-code-switched Spanish sentence or was a Spanish sentence that had an English noun phrase at the beginning. The two types of Prime Structure trials and the two types Code-switched trails combine for a total of four different conditions.



FILLERS As was the case for all the experimental trials, half of the fillers consisted of transitive events in both the prime (sentence and picture) and in the target picture. The other half of the fillers consisted of intransitive events. The intransitive events always involved two people in the prime sentence and picture and the target picture. Unlike the experimental trials, the fillers also included prime sentences in Spanish with a code-switch at another point in the sentence and sentences that were fully in English. The fillers had verbs below the target picture in either Spanish or English. For half of the fillers, the sentence and picture on the prime screen did not match. These mismatches were equally divided over transitive and intransitive fillers. The experimental trials did not include any mismatches.

EXPERIMENTAL LISTS AND PRACTICE TRIALS We created four experimental lists that counterbalanced the four conditions. Participants were (pseudo-)randomly assigned to one of these lists. For each participant the order of the list was (pseudo-)randomized with a maximum of two consecutive trials or fillers. Each list consisted of 60 trials and 60 fillers. We preregistered 80 trials and 80 fillers, but reduced these numbers after piloting the experiment showed that it took participants too long. Participants therefore saw 15 items in each of the 4 conditions.

We created 8 unique practice trials. Half of these had the same configuration as the experimental trials, while the other half had the same configuration as the fillers. The practice trials had the same percentage of mismatches as the main experiment. Of the eight practice trials, one transitive and one intransitive were mismatches. The practice trials were the same for all participants.




(a) *Prime screen* (b) *Target screen*

**Figure 6.2:** Example of a prime screen (on the left) and an associated target screen (on the right). On experimental trials, the recording of the Spanish active or passive prime sentence that accompanied the prime screen was either code-switched (e.g. "The witch golpea al nadador.") or not (e.g. "La bruja golpea al nadador.").

#### 6.3.1.2 Procedure

In the main part of the experiment, participants first listened to a spoken prime sentence while looking at a picture (See Figure 6.2a). To make sure that participants paid attention to these, they answered the question whether the sentence and picture matched. Next, they were asked to type a one-sentence description of the target picture, using the verb that was displayed below the picture (See Figure 6.2b). To elicit a target sentence in the intended target language, the language of the instructions that asked participants to use the verb below the picture was always the same as the language of that verb. However, we did not instruct participants explicitly to use that language.

Before the start of the main experiment, participants went through eight practice trials. On these trials, participant received two types of feedback that they did not receive on trials in the main part of the experiment. Firstly, we showed participants if they correctly answered the question whether the prime picture and spoken sentenced matched. Secondly, after typing target sentences, we showed participants correct examples of sentences they could have typed.

After the main experiment, participants filled in the Bilingual Language Profile (Birdsong, Gertken, & Amengual, 2012) and the Bilingual Code-Switching Profile (Olson, 2022). The experiment was conducted online using the Gorilla Experiment Builder (https://www.gorilla.sc, Anwyl-Irvine, Massonnié, Flitton, Kirkham, & Evershed, 2020). Participants were required to use Chrome browser on a laptop or desktop computer to take the experiment.



#### 6.3.1.3 Participants

Based on the available budget, the small interaction effect we found in the simulated experiment, and the sample size recommendations for small interactions with structural priming effects from Mahowald, James, Futrell, and Gibson (2016), we recruited 200 participants through Prolific (https://www.prolific.com). All participants were adult Spanish-English bilinguals from the US. We excluded 10 participants from the analysis. As preregistered, we excluded 3 participants because they reported having started to learn English after the age of 12, and 4 other participants because they reported having started to learn Spanish after the age of 8 in the Bilingual Language Profile. A further 3 participants were not included in the analysis because all their responses were coded as “other”. All participants answered at least 70% of the picture-sentence matching questions correctly. The analysis thus included data from 190 participants, aged 18 to 60 (mean age 33), whose age of acquisition of Spanish ranged from 0 (i.e., from birth) to 8 with a mean of 0.6 and whose age of acquisition of English ranged from 0 to 12 with a mean of 2.4.

#### 6.3.1.4 Coding of target sentences

Our analysis only included target sentences that were coded as active or passive and that were fully in English or were in English with code-switching to Spanish. In the next two paragraphs we describe the details of how coding was done.



CODING OF SENTENCE STRUCTURE As preregistered[1], we coded target sentences as "active", "passive" or "other". Active sentences consisted of a subject noun phrase, followed by a verb, followed by an object noun phrase. Passive sentences consisted of a subject noun phrase, followed by a form of the verb "to be", followed by a past participle, followed by a "by"-phrase. We included sentences with noun phrases consisting of pronouns, sentences with complex noun phrases (e.g., "the waitress kicked the clown's arm"), sentences with typos or other minor errors, sentences that use a different transitive verb, sentences that use incorrect or vague nouns (e.g. "the guy"), and sentences with an added auxiliary (e.g., "the nun does kick the prisoner") or with negation (e.g., "the pirate does not chase the sailor"). We also interpreted the preregistration's description of passive sentences as having a form of "to be" to include informal equivalents of "to be", so we included sentences such as "the clown gets kicked by the waitress." All remaining responses (including passives in which the "by"-phrase is omitted) were coded as "other".

CODING OF SENTENCE LANGUAGE We were only interested in analysing *cross-language* structural priming from Spanish to English. Therefore, all target sentences that were fully in Spanish were coded as "other". This means we included target sentences that were either fully in English or that were in English with code-switching to Spanish.

Our preregistration did not define explicitly when a code-switched target sentence should be considered as an English or a Spanish sentence. Target sentences were elicited with the instruction to use the verb below the picture. For experimental trials, this verb was always in English. Because of this, we decided to code those

[1]See the preregistration here: `https://aspredicted.org/WQG_Z9S`

code-switched target sentences as English sentences with code-switching to Spanish, when the main verb was in English.

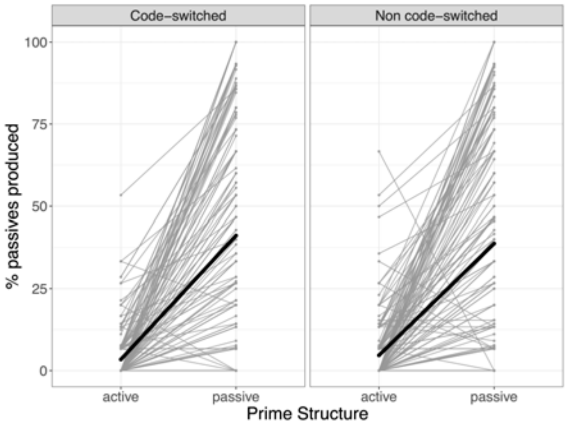



**Figure 6.3:** Results of Behavioral Experiment, where code-switches consisted of a determiner and noun at beginning of prime sentence. The thick black lines visualize the priming effect across all analyzed trials by connecting the percentage of passives responses after active primes to the percentage of passive responses after passive primes. The thin grey lines show the same for each individual participant.



### 6.3.2 Results

We analysed 94% of the responses on code-switched trials, and 93% of responses on non-code-switched trials. On code-switched trials, 41.2% of sentences were passives after a passive prime, while 3.4% of sentences were passive after an active prime. On non-code-switched trials, 38.8% of sentences were passives after a passive prime, while 4.7% of sentences were passive after an active prime. Figure 6.3 visualizes these priming effects.

**Table 6.3:** Fixed effects summary for the logistic mixed-effects model ($N = 10,632$): estimates with 95% confidence intervals and $p$-values for each predictor.

| Predictor | Est. | 95% CI | $p$-value |
|---|---|---|---|
| INTERCEPT | −2.70 | [−3.02, −2.39] | < 0.001 |
| PRIMESTRUCTURE | 1.91 | [1.7, 2.12] | < 0.001 |
| CODE-SWITCHED | −0.05 | [−0.15, 0.03] | 0.258 |
| CODE-SWITCHED × PRIMESTRUCT. | 0.15 | [0.06, 0.25] | 0.002 |

#### 6.3.2.1 Analysis



As preregistered[2], we analysed the results largely in the same way as the simulation results. We used a binary dependent variable, IS_PASSIVE, that indicates whether participants produced a passive sentence (1), or not (0). We fit a logistic linear mixed effects model, using a logit link function, with the two predictors of interest, CODE-SWITCHED (No = −0.5, Yes = 0.5) and PRIMESTRUCTURE (Active = −0.5, Passive = 0.5), and their interaction. We included random intercepts for items and participants, as well as by-participant and by-item random slopes for PRIME STRUCTURE and CODE-SWITCHED and their interaction, and correlations between random effects.

As expected based on the literature, the analysis showed a significant effect of PRIME STRUCTURE (Est. = 1.91 (95% CI: [1.70, 2.12]), $p \leq 0.001$) on the production of passives, indicating a Spanish to English cross-language priming effect. Importantly, the analysis also revealed a significant positive interaction between CODE-SWITCHED condition and PRIME STRUCTURE (Est. = 0.15 (95% CI: [0.06, 0.25]), $p = 0.002$) showing that priming in the participants was stronger after processing a code-switched English noun phrase at the beginning of the prime sentence compared to fully Spanish prime sentences.

### 6.3.3 Discussion

The results of our cross-language priming experiment are in line with those of the simulated version of the experiment. Participants produced more English passives after processing Spanish prime sentences that were passive than after those that

[2]See the preregistration here: `https://aspredicted.org/WQG_Z9S`

were active, and this cross-language priming effect was stronger when there was a code-switched English determiner and noun at the beginning of the Spanish prime sentence.

## 6.4 General Discussion

Under an implicit learning account, as instantiated in the Bilingual Dual-path model, structural priming occurs when prediction error during processing of a prime sentence leads to learning in the language system related to the syntactic structure of that prime sentence. When structural priming occurs between two different languages, the syntactic structure involved must be in some way shared between those two languages in the language system of a bilingual. Otherwise, processing of a prime in one language could not lead to changes in production of a target sentence in the bilingual's other language.



In line with earlier findings (see Section 6.1.2 and 6.1.3.2), we found cross-language structural priming in both the simulated and the behavioral experiments. Crucially, we also found that a code-switch in the prime sentence can lead to increased cross-language priming compared to a single-language prime sentence. Under an implicit learning account, this means that processing of a code-switched prime sentence can result in increased prediction error and subsequent error-based learning that involves a syntactic representation that is shared between the prime and target languages. What aspect of such a representation could be updated when a prime sentence is code-switched but not when it is in a single language? A possibility is that the bilingual language system is learning the statistics of code-switches occurring in sentences linked to the syntactic representation involved, and more specifically, in what position in the syntactic structure a code-switch can occur. From the perspective of word-by-word prediction, the language system might be learning transitional probabilities between words of the two languages, in the context of sentences that have the shared syntactic structure of the prime sentence.

A related possibility, under the Adaptive Predictability hypothesis (Valdés Kroff &

Dussias, 2023), is that the language system is learning the statistics of code-switches as cues of infrequent upcoming language. Unlike the results of Tomić and Valdés Kroff (2022), however, the infrequent upcoming language does not concern infrequent lexical items, but infrequent passive sentence structure.

### 6.4.1 Limitations and future work

#### 6.4.1.1 How well did the simulations predict the experimental results?



When comparing Figure 6.1 and Figure 6.3, that visualize the results of the simulated and behavioral experiments, respectively, the results might not seem to correspond closely. The main difference lies in the strength of the overall priming effect. We think that this can be explained in part by the lexical boost effect (for an overview see Mahowald et al., 2016) that increases the priming effect in people but not in the model, which is a known limitation in the model (Chang et al., 2006). However, the size of the interaction effect between code-switching and priming is similar between the two results.

#### 6.4.1.2 Experience with code-switches

An important difference between the participants and the model is that the former have likely experienced Spanish-English code-switching before, whereas the simulated participants did not encounter any code-switching during training. There is reason to expect, however, that this does not necessarily cause differences in how they processed code-switched prime sentences. The simulations conducted by Tsoukala, Broersma, et al. (2021) demonstrated that the model is able to produce human-like code-switches, even when it is not trained on code-switched input. In addition, it is one and the same mechanism that processes and produces sentences in the (Bilingual) Dual-path model. It is therefore likely that the model can process code-switched sentences in a human-like way, without training on such sentences.

#### 6.4.1.3 Production of code-switches in target sentences

As mentioned above, one of the original purposes of the Bilingual Dual-path model was to study the production of code-switches (Tsoukala, Broersma, et al., 2021; Tsoukala, Frank, et al., 2021). In our own simulated experiments, however, the model was not configured to produce code-switches. The human participants, on the other hand, were allowed to code-switch when producing target sentences. They were not explicitly asked to do so, but during the practice phase of the experiment, the participants saw code-switches among the examples of target sentences that they could have typed. Exploratory analyses of our data could clarify whether cross-language structural priming did not only increase after code-switched prime sentences, but is also increased when participants produced code-switches in their target sentences. Further simulated experiments could then investigate if this also occurs in the model, when it is configured to allow code-switching as it produces target sentences.



In addition, exploratory analyses could also reveal whether earlier reports of priming of code-switches themselves are confirmed in the data from our human participants. Based on what Fricke and Kootstra (2016); Kootstra et al. (2020) reported, we would expect more code-switches in the target sentences participants produced after a code-switched compared to a non-code-switched prime sentence.

## 6.5 Conclusion

Taken together, our modeling and behavioral results suggest that processing code-switches in a prime sentence can result in increased prediction error, which in turn can lead to increased implicit learning of shared syntactic representations, resulting in stronger cross-language structural priming. These results also demonstrate for the first time that the Bilingual Dual-path model can be used to predict novel psycholinguistic effects in human participants.

## 6.6 Acknowledgements

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# 7

# General discussion



This thesis investigated whether bilingual syntax can be explained as error-based implicit learning. The thesis first introduced the Bilingual Dual-path model (**Chapter 2**) and then used that model to examine bilingual phenomena in sentence processing and production (**Chapters 3 to 6**), and in acquisition (**Chapters 4 and 5**). In **Chapter 6**, the model was used successfully to predict the outcome of a new online structural priming experiment with human participants.

This final chapter first summarizes the findings of the thesis. It then discusses theoretical implications, limitations and directions for future research, before ending the thesis with concluding remarks.

## 7.1 Summary of the main findings

**Chapter 3** investigated whether implicit learning can account for cross-language structural priming. It combined the monolingual account of structural priming with the implemented Bilingual Dual-Path model that was introduced in Chapter 2. Instances of the model were trained to be used as participants in simulated experiments. These simulated cross-language structural priming experiments showed that an error-driven implicit learning account, as instantiated in the Bilingual Dual-path model: (1) can explain experimental findings of structural priming between different languages for several language pairs, (2) accounts for cross-language structural priming being weaker than within-language priming, (3) allows for priming between structures with different surface word order as has been reported in the literature, and (4) predicts structural priming between languages that are typologically different.

**Chapter 4** addressed contrasting findings in the literature on whether cross-language structural priming is modulated by proficiency or exposure, which would be the case according to the developmental account proposed by Hartsuiker and Bernolet (2017). This account, however, predicts such a modulating effect in *sequential*, but not in *simultaneous* bilinguals. The chapter found that proficiency or exposure did not affect the cross-language priming effect (that was found in **Chapter 3**) in simulated simultaneous bilinguals, in line with what was found in human participants (Kutasi et al., 2018).



**Chapter 5** tested whether ERPs in L2 learners in response to syntactic violations can be explained as implicit learning. A version of the Dual-path model was used that was created to simulate event related potentials in monolingual sentence processing (Fitz & Chang, 2019). The chapter extended this model to simulate ERPs in *bilingual* sentence processing. The results showed that the model can account for how ERPs in response to syntactic violations in second-language learning develop during learning. In addition, the model also simulated the influence of cross-language similarity on such ERPs. However, in contrast with human participants, simulated participants showed a small P600 response to gender violations, which were unique to the L2. It remains to be determined if this is because of how this grammatical feature is encoded in the model (see Section 7.3).

**Chapter 6** investigated whether code-switching and cross-language structural priming might interact in the model and in humans. It first showed that structural priming of active and passive structures from Spanish to English increased with code-switching in the prime compared to non-code-switched primes in the Bilingual

Dual-path model. This was only the case if the code-switch consisted of a code-switched determiner and noun at the beginning of the sentence, but not for three other types of code-switches. Secondly, the results of an online priming experiment revealed that the effect of code-switching on cross-language structural priming that was found in the model, also occurred in Spanish-English bilingual participants. This demonstrated for the first time that the Bilingual Dual-path model can successfully predict new experimental results.

## 7.2 Theoretical implications

The reported research has increased our understanding of bilingual syntax by showing that: (1) cross-language structural priming, (2) the effect of code-switching on cross-language structural priming, and (3) the development of L2 ERP responses to syntactic violations from an N400 to a P600, can all be accounted for by implicit learning driven by prediction error. Building on earlier work with the Bilingual Dual-path model (see Chapter 2), the thesis has provided further support for this implicit learning account by demonstrating that it extends to the language system of people who use two different languages. This section discusses the implications this has for broader debates in psycholinguistics, (e.g., on language prediction) and beyond (e.g., on language change).



### 7.2.1 How and why do we predict upcoming language?

It has become less and less controversial that people predict language input. However, the jury is still out on how and why we do this. Two main accounts are prevalent in the literature that see prediction either as *predictive coding* that is part of a hierarchical comprehension process or as part of a *learning* process (Ryskin & Nieuwland, 2023).

On the one hand, predicting upcoming language has been explained using a domain general *predictive coding* framework (Rao & Ballard, 1999). Applied to language comprehension, this framework has higher levels of representation (e.g., meaning and high-level statistical information) transmitting top-down predictions to lower levels (e.g., word forms and sounds), while bottom-up prediction error flows back from lower to higher levels of representation (e.g., Kuperberg & Jaeger, 2016; Wang et al., 2023).

On the other hand, the main function of prediction is seen as an essential step in an *error-based implicit learning* process. The findings in this thesis further support this implicit learning account. The simulations in Chapter 3, 4, and 6 show that cross-language structural priming can be explained as implicit learning driven by prediction error, during the processing of prime sentences. Additionally, ERP effects in language processing are some of the main sources of evidence for prediction in language. Fitz and Chang (2019) have shown that language ERPs in monolingual sentence processing can be interpreted as implicit learning. Under this account, ERPs reflect brain activity that results from prediction error propagating through the language system during sentence comprehension. Prediction error can occur in the lexical-semantic system first, leading to an N400, before propagating to the syntactic system, where it can result in a P600. Chapter 5 has demonstrated that it is also implicit learning based on prediction error that drives ERPs in response to syntactic violations in L2 learning.



### 7.2.2 Comprehension and production

The psycholinguistic phenomena that were investigated in this thesis are relevant to the related debates on how sentence comprehension and production are connected in the language system, how representations are shared between comprehension and production, and how they should be studied together (e.g., Ferreira & Swets, 2017; MacDonald, 2013; Morgan, von der Malsburg, Ferreira, & Wittenberg, 2020; Pickering & Garrod, 2004; Segaert, Menenti, Weber, Petersson, & Hagoort, 2012). Structural priming, for instance, has been interpreted as a form of audience design (Clark & Murphy, 1982) or interactive alignment (Pickering & Garrod, 2004). People engage in interactive alignment when they adapt their language production to optimize comprehension by the addressee. This could describe structural priming, since it involves reproducing syntactic structures that a conversation partner has recently used.

Interactive alignment and audience design also occur between different languages and when different languages are mixed. Findings of cross-language structural priming demonstrate that people adapt their syntactic production in one language to recent experience of syntax in another language. Code-switching has also been studied in the context of interactive alignment. In an experiment using a confederate-scripted dialogue paradigm, Kootstra et al. (2010) showed that participants aligned their code-switching patterns with the confederate's code-switching. In a corpus study on code-switching in dialogue, Myslín and Levy (2015) showed that bilinguals engage in audience design in their code-switching. They take into account the language skill of their interlocutor in their language choice to improve intelligibility of sections of speech that are particularly informative.

The thesis has extended the earlier work using the Dual-path model to further findings in L2 learning, and in bilingual comprehension processing and production. In doing so, it has provided additional validation of the P-chain theory (Dell & Chang, 2014), that brings together comprehension, production and acquisition in a single implicit learning framework as instantiated in the (Bilingual) Dual-path model. The bilingual simulations in this thesis highlight the unification of processing, production and acquisition in showing that these processes interact for two languages in the bilingual version of the model, in the same way as one language in the original model. Human-like cross-language structural priming, L2 ERPs, and processing of code-switches were successfully simulated using a bilingual version of the model that differs only minimally from the monolingual model (see Chapter 2). This shows that one and the same error-based implicit learning mechanism, as instantiated in the Bilingual Dual-path model, can account for a range of psycholinguistic phenomena that cover both comprehension and production.



### 7.2.3 Shared and abstract syntax

Cross-language structural priming has been interpreted as evidence for shared syntax in bilinguals (Hartsuiker et al., 2004), since processing of the structure in one language affects production of sentence structure in the other. The cross-language structural priming results presented in this thesis reveal the same evidence for shared syntax in the Bilingual Dual-path model. Intra-sentential code-switching that consists of more than the insertion of a single word involves the syntax of both languages of a bilingual. Earlier work has shown that the model can *produce* human-like code-switches (Tsoukala, Broersma, et al., 2021), and this thesis has demonstrated that it can also *process* code-switches in a human-like way (see Chapter 6).

Syntax is considered abstract when it is not necessarily connected to the mappings between specific meanings and words (e.g., Chang et al., 2006). Structural priming has been shown to involve representations that are specified for syntactic information but not for lexical, semantic, or phonological information, and has therefore been interpreted as evidence for abstract syntax (e.g., Bock, 1986; Branigan & Pickering, 2017). However this evidence has also been criticized, for example by arguing that the abstract nature of representations involved in structural priming can be questioned by taking into account effects of animacy, semantic event structure, shared morphology, information structure, or rhythm (e.g., Hare & Goldberg, 2020; Ziegler, Bencini, Goldberg, & Snedeker, 2019). The Dual-path model (Chang, 2002; Chang et al., 2006) was developed as a model of how abstract knowledge and concrete language experience come together in syntactic acquisition and production. The cross-language priming simulations in this thesis show that syntax in the bilingual version of the model also abstracts away from a specific language, as processing of sentence structure in one language affects production of sentence structure in the other, without any lexical overlap between the prime and target sentences.



### 7.2.4 Language change

Error-based implicit learning explains structural priming as a reflection of long term changes in the language system of an individual. This thesis has shown that cross-language structural priming can also be explained using that same learning mechanism. This means that when a bilingual processes a sentence in one language, this can lead to long term changes in their language system for the other language. Subsequently, the changed language system leads to changed language production by this bilingual. In turn, that changed language production can affect the language system of other speakers of that language through within-language structural priming, leading to changes in the language system of those other speakers of the language. This supports the idea that cross-language structural priming is an underlying mechanism of contact-induced language change (Kootstra & Şahin, 2018; Kootstra & Muysken, 2019; van Dijk & Hopp, 2025).

## 7.3 Limitations and future directions

This section first discusses limitations and related further work that follows up on findings in specific chapters in this thesis. The rest of the section discusses directions for future research that follow from the findings across the thesis.

Chapter 4 investigated whether proficiency of exposure affect cross-language structural priming. However, it was limited to simulating *simultaneous* bilinguals. An obvious study to follow up that chapter, would be to simulate *sequential* bilinguals, as was done in Chapter 5. It could then be tested whether L2 proficiency or exposure does modulate the strength of cross-language structural priming in those simulated *sequential* bilingual participants, unlike in the *simultaneous* bilinguals that were simulated in this thesis. That kind of modulating effect would be expected based on the developmental account of Hartsuiker and Bernolet (2017) and findings from experimental studies by, for example, Bernolet et al. (2013).



Chapter 5 reported on simulations of ERPs in response to syntactic violations in L2 learning. The *bilingual* investigation presented in this chapter uncovered a limitation in the *monolingual* version of the Dual-path model: At present, it does not successfully simulate the clear P600 effects in response to syntactic gender violations that are found in people (e.g., Antonicelli & Rastelli, 2022). A different implementation of gender in the model's language input will be required to address this issue. Number and tense violations did yield P600 effects. It therefore seems likely that a P600 effect would be reproduced with an implementation of syntactic gender that is in line with the implementation of tense and number. If so, this would suggest that such an implementation is a better reflection of processing of syntactic gender in humans than the current implementation. If this is indeed the case for the monolingual Dual-path model, then simulations can be conducted to determine if processing of gender violations in the Bilingual Dual-path model is in line with results for human participants (e.g., Foucart & Frenck-Mestre, 2011).

Chapter 6 investigated whether cross-language structural priming would increase with code-switching in the prime sentences, compared to primes without code-switching. Because of the small interaction between code-switch condition and prime structure that was found in the simulated experiments in this chapter, the human experiment only tested the effect of one specific code-switch, with an English noun phrase at the beginning of the Spanish prime sentence. It is therefore not known if other code-switches would result in an interaction with structural priming or not. Consequently, it is not clear that the interpretation of the interaction effect in the model, based on the specific pattern of results for different code-switches, holds for people.



The small interaction found in people suggests that testing of similarly large numbers of participants would be required to determine if the pattern of results of the four simulated experiments holds. However, the individual differences in the cross-language priming effect (see Figure 6.3) suggest a possible solution for this problem. Smaller sample sizes might be sufficient if characteristics of participants can be found that are related to the size of the interaction effect. Possible candidates for such characteristics could be code-switching behavior and experience and/or relative proficiency in the two languages (e.g., Beatty-Martínez & Dussias, 2017; Valdés Kroff, Guzzardo Tamargo, & Dussias, 2018). Participants answered a range of questions on these subjects in the surveys after the main experiment. The data from these surveys can be used as predictors in further exploratory analyses, which fall outside of the scope of this thesis.

### 7.3.1 From short-term effects to long-term learning

A defining characteristic of the implicit learning mechanism studied in this thesis is that it explains apparently short-term effects such as structural priming and ERPs as the result of long-lasting changes in the language system.

However, evidence that structural priming in the Dual-path model is long-term in the same way as in humans is limited. So far, only a simulated experiment by Chang et al. (2006) has shown that structural priming persists over 4 or 10 filler trials. Cumulative structural priming, where the production of a structure increases due to priming as an experiment progresses, has been demonstrated in people's L1 and L2 (e.g., Jaeger & Snider, 2008; Kaan & Chun, 2018) and bilinguals' two languages (Kootstra & Doedens, 2016; van Dijk & Hopp, 2025) but not in the model. The same is true for long-term priming as measured by comparing the production of a structure immediately before and after an experiment where that structure is primed exclusively (e.g., Fazekas et al., 2020; Kaschak, 2007; van Dijk & Hopp, 2025) or by comparing separate experimental sessions with a month in between (Heyselaar & Segaert, 2022). Although it seems evident that error-based learning, as instantiated in the Dual-path model, leads to cumulative and long-term priming, this remains to be demonstrated in the model. This becomes especially important when trying to tease apart how verb-dependent biases for specific structures in different languages (and the inverse priming effects that result from these biases) interact with cumulative and long-term cross-language structural priming (van Dijk & Hopp, 2025). It is also necessary to simulate such long term priming effects to provide more concrete insight in the role that error-based implicit learning plays in contact-induced language change.



Chapter 5 took a long-term perspective in a different way, by investigating how ERPs in response to syntactic violations develop over time in L2 learning. This has opened the door to further work on L2 learning. The Bilingual Dual-path model can, for instance, be used to simulate findings on how L2 sentence processing can become more like L1 processing as reflected in within-language structural priming in the L2 (for an overview, see Jackson, 2018). The longitudinal simulation paradigm from Chapter 5, with repeated simulated experiments while training of the model progressed, could also be applied there to give insight into long-term learning.

### 7.3.2 Simulating ERPs during processing of code-switches

The ERP simulations from Chapter 5 could be combined with the investigations on processing of code-switches from Chapter 6. This could shed further light on how prediction error that results from processing code-switches leads to increased implicit learning of syntax, which in turn leads to increased cross-language structural priming. For those code-switched prime sentences that were followed by target sentences with the same structure, we would expect to see increased learning in the hidden layer that we interpreted in Chapter 5 as corresponding to a P600 effect. This could open the door to simulating results from studies that found sentence-level ERP effects during the processing of code-switches such as the studies by Moreno et al. (2002) and Van Der Meij et al. (2011) (see Section 6.1.1).



## 7.4 Concluding remarks

This thesis has investigated bilingual syntax as error-based implicit learning. The results show that such a learning mechanism, instantiated in the Bilingual Dual-path model, accounts for experimental findings on cross-language structural priming and ERPs in L2 learning, and that the model can predict new experimental results on how processing code-switches affects cross-language structural priming. Thus, the thesis has furthered our understanding of a range of bilingual phenomena that play a central role in the psycholinguistic investigation of bilingual syntax, by presenting a plausible underlying mechanism that explains them. At the same time, the thesis has provided further validation for that mechanism.

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# Research Data Management

## Ethical approval and consent

An exempt determination was received from the Institutional Review Board of the Research Division of Research Operations at the University of Florida in Gainesville, Florida, USA, for the human data collection in the US that is reported in Chapter 6 of this thesis (Protocol #: ET00023555). That exemption authorized us to conduct that research. The data collection followed an informed consent procedure that was established by the Institutional Review Board at the University of Florida.

## Personal data

Personal data was collected online using Prolific (https://www.prolific.com) and Gorilla Experiment Builder (https://www.gorilla.sc). Typed responses were collected, consisting of single sentences, of participants during the experiment and they filled out surveys on their language background and use. Personal information was obtained, including participants' gender, and age, education, and information about participants' language use. The names of participants were only needed for administrative purposes and they were known only to Prolific. It was necessary to collect personal data, because individual factors such as language proficiency, exposure, and use could explain individual differences in the effects under investigated in the thesis. To this end, it was crucial to collect detailed information at the personal level. No more personal data was collected than necessary: The level of detail in the data on language background and, which is the most personal data that was collected, is based on previous research that explores the effects of such factors bilingual language processing.

So far, only age and age of acquisition of English and Spanish of the participants have been analyzed to report general characteristics, i.e. ranges and means, of the participant sample and to ensure that participants met the selection criteria in terms of age of acquisition. Because of the limited time for the PhD project, the personal data that was collected has not yet been analyzed any further. Exploratory analyses of these data are planned for the future. This data will be stored for 10 years. No personal data will be made publicly available.

The final dataset that was analyzed did not contain name, date of birth, address, contact information, age, gender, or outcomes for language proficiency, exposure, and use. They only contained ID numbers (which were different from the ones that link the participants to their personal data on Prolific), coding of sentences produced by participants, and data on experimental conditions. The final dataset was stored on a fully encrypted Radboud University laptop for analysis and encrypted and backed up automatically on SURF Drive. The computationally generated data used throughout the thesis was stored on Ponyland and on a fully encrypted Radboud University laptop and encrypted and backed up automatically on SURF Drive.

The raw data, metadata and documentation data associated with this thesis has been archived in the Radboud Data Repository (RDR), and will be stored there for a minimum of 10 years. The data has not been shared with any other researchers other than adding them to the RDR, that is accessible by my supervisors. The human data has been archived in the RDR for scientific integrity, but it cannot be shared for reuse by other researchers.

Modeling code for Chapters 3 to 6 is publicly available on GitLab:
https://gitlab.com/yhkhoe/bilingual-dual-path

Syntax files for Chapter 3 and 4 are publicly available on GitHub:
https://github.com/khoe-yh/cross-lang-struct-priming
Syntax files for Chapter 5 are publicly available on OSF:
https://osf.io/h6c52/
Syntax files for Chapter 6 will be made publicly available after publication.

# Author contributions

## Chapter 1 and 7

These chapters were written by Yung Han Khoe (YHK) and were revised by him based on feedback provided by Stefan Frank (SF), Gerrit Jan Kootstra (GJK), and Rob Schoonen (RS).

## Chapter 2

This chapter is based on the abstract and sections 1, 2, 3.1, 3.2 and 3.4 of:
Khoe, Y. H., & Frank, S. L. (2024).
The Bilingual Dual-path model: Simulating bilingual production, processing, and development.
*Linguistic Approaches to Bilingualism*.

Those parts of the manuscript were written by Yung Han Khoe (YHK) and were revised by him based on feedback provided by SF, and reviewers.

The chapter was written by YHK and was revised by him based on feedback provided by SF, GJK, RS.

## Chapter 3

This chapter is based on:
Khoe, Y. H., Tsoukala, C., Kootstra, G.J., Frank, S. (2023).
Is structural priming between different languages a learning effect? Modelling priming as error-driven implicit learning,
*Language, Cognition and Neuroscience*, 38, (pp. 537-557)

The study was designed and performed by YHK, in collaboration with and under supervision of SF, Chara Tsoukala (CT), GJK, and RS. The manuscript was written by YHK and was revised by him based on feedback provided by SF, CT, GJK, RS, and reviewers.

This chapter is also based on section 4 of:
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That part of the manuscript was written by YHK and was revised by him based on feedback provided by SF, GJK, RS, and reviewers.
The study was designed and performed by YHK, in collaboration with and under supervision of SF, GJK, and RS.

The chapter was written by YHK and was revised by him based on feedback provided by SF, GJK, RS.

## Chapter 4

This chapter is based on:
Khoe, Y. H., Kootstra, G.J., Schoonen, R., Frank, S. (2021).

Simulating proficiency and exposure effects on cross-language structural priming in simultaneous bilinguals,
In Stewart, T. C. (Ed.). *Proceedings of the 19th International Conference on Cognitive Modelling*, (pp. 150-156)

The study was designed and performed by YHK, in collaboration with and under supervision of SF, GJK, and RS.
The manuscript was written by YHK and was revised by him based on feedback provided by SF, GJK, RS, and reviewers.

The chapter was written by YHK and was revised by him based on feedback provided by SF, GJK, RS.

## Chapter 5

This chapter is based on:
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A neural network simulation of event-related potentials in response to syntactic violations in second-language learning.
*Proceedings of the 21st International Conference on Cognitive Modelling*

and on:
Verwijmeren, S., Frank, S.L., Fitz, H., Khoe, Y. H. (2024).
Simulating event-related potentials in bilingual sentence comprehension: syntactic violations and syntactic transfer.
*Proceedings of the 22nd International Conference on Cognitive Modelling*

The studies were designed and performed by Stephan Verwijmeren (SV), in collaboration with and under supervision of YHK, SF, and Hartmut Fitz (HF).

The first ICCM paper was written by SV, and was revised by him based on feedback provided by YHK, SF, HF, and reviewers.

The second ICCM paper was written by SV, YHK, and SF, and was revised by them based on feedback provided by HF and reviewers.
This paper was based on a Master's thesis that was written by SV and was revised by him based on feedback provided by YHK, SF, and HF.

The chapter was written by YHK and was revised by him based on feedback provided by SF, GJK, and RS.

## Chapter 6

The study was designed and performed by YHK, in collaboration with and under supervision of Edith Kaan (EK), SF, GJK, and RS.
The chapter was written by YHK and was revised by him based on feedback provided by EK, SF, GJK, and RS.

# Summary

This thesis investigated whether bilingual syntax can be explained as error-based implicit learning. The thesis first introduced the Bilingual Dual-path model (**Chapter 2**) and then used that model to examine bilingual phenomena in sentence processing and production (**Chapters 3 to 6**), and in acquisition (**Chapters 4 and 5**). In **Chapter 6**, the model was used successfully to predict the outcome of a new online structural priming experiment with human participants.

**Chapter 3** investigated whether implicit learning can account for cross-language structural priming. It combined the monolingual account of structural priming with the implemented Bilingual Dual-Path model that was introduced in Chapter 2. Instances of the model were trained to be used as participants in simulated experiments. These simulated cross-language structural priming experiments showed that an error-driven implicit learning account, as instantiated in the Bilingual Dual-path model: (1) can explain experimental findings of structural priming between different languages for several language pairs, (2) accounts for cross-language structural priming being weaker than within-language priming, (3) allows for priming between structures with different surface word order as has been reported in the literature, and (4) predicts structural priming between languages that are typologically different.

**Chapter 4** addressed contrasting findings in the literature on whether cross-language structural priming is modulated by proficiency or exposure, which would be the case

according to the developmental account proposed by Hartsuiker and Bernolet (2017). This account, however, predicts such a modulating effect in *sequential*, but not in *simultaneous* bilinguals. The chapter found that proficiency or exposure did not affect the cross-language priming effect (that was found in **Chapter 3**) in simulated simultaneous bilinguals, in line with what was found in human participants (Kutasi et al., 2018).

**Chapter 5** tested whether ERPs in L2 learners in response to syntactic violations can be explained as implicit learning. A version of the Dual-path model was used that was created to simulate event related potentials in monolingual sentence processing (Fitz & Chang, 2019). The chapter extended this model to simulate ERPs in *bilingual* sentence processing. The results showed that the model can account for how ERPs in response to syntactic violations in second-language learning develop during learning. In addition, the model also simulated the influence of cross-language similarity on such ERPs. However, in contrast with human participants, simulated participants showed a small P600 response to gender violations, which were unique to the L2. It remains to be determined if this is because of how this grammatical feature is encoded in the model (see Section 7.3).

**Chapter 6** investigated whether code-switching and cross-language structural priming might interact in the model and in humans. It first showed that structural priming of active and passive structures from Spanish to English increased with code-switching in the prime compared to non-code-switched primes in the Bilingual Dual-path model. This was only the case if the code-switch consisted of a code-switched determiner and noun at the beginning of the sentence, but not for three other types of code-switches. Secondly, the results of an online priming experiment revealed that the effect of code-switching on cross-language structural priming that was found in the model, also occurred in Spanish-English bilingual participants. This demonstrated for the first time that the Bilingual Dual-path model can successfully predict new experimental results.

This thesis has investigated bilingual syntax as error-based implicit learning. The results show that such a learning mechanism, instantiated in the Bilingual Dual-path model, accounts for experimental findings on cross-language structural priming and ERPs in L2 learning, and that the model can predict new experimental results on how processing code-switches affects cross-language structural priming. Thus, the thesis has furthered our understanding of a range of bilingual phenomena that play a central role in the psycholinguistic investigation of bilingual syntax, by presenting a plausible underlying mechanism that explains them. At the same time, the thesis has provided further validation for that mechanism.

# Nederlandse samenvatting

In dit proefschrift werd onderzocht of tweetalige syntaxis verklaard kan worden als foutgebaseerd impliciet leren. Eerst werd het tweetalige dual-path model geïntroduceerd (**hoofdstuk 2**) en vervolgens werd dat model gebruikt om tweetalige verschijnselen te onderzoeken in zinsverwerking en -productie (**hoofdstukken 3 tot en met 6**) en in zinsverwerving (**hoofdstukken 4 en 5**). In hoofdstuk 6 werd het model met succes gebruikt om de uitkomst van een nieuw online structureel priming-experiment met menselijke deelnemers te voorspellen.

**Hoofdstuk 3** onderzocht of impliciet leren structurele priming tussen twee talen kan verklaren. Het combineerde de monolinguale verklaring van structurele priming met het geïmplementeerde Bilingual Dual-Path-model dat in hoofdstuk 2 werd geïntroduceerd. Instanties van het model werden getraind om te worden gebruikt als deelnemers aan gesimuleerde experimenten. Deze gesimuleerde structurele priming-experimenten toonden aan dat een foutgestuurde impliciete leerverklaring, zoals geïnstantieerd in het Bilingual Dual-Path-model: (1) de experimentele bevindingen van structurele priming tussen verschillende talen voor meerdere taalparen kan verklaren, (2) verklaart dat cross-language structurele priming zwakker is dan priming binnen één taal, (3) priming mogelijk maakt tussen structuren met een verschillende oppervlaktewoordvolgorde, zoals gerapporteerd in de literatuur, en (4) structurele priming voorspelt tussen talen die typologisch verschillend zijn.

**Hoofdstuk 4** behandelde tegenstrijdige bevindingen in de literatuur over de vraag of structurele priming tussen twee talen gemoduleerd wordt door vaardigheid of blootstelling, wat het geval zou zijn volgens de ontwikkelingstheorie van Hartsuiker en Bernolet (2017). Deze theorie voorspelt echter een dergelijk modulerend effect bij sequentiële, maar niet bij simultane tweetaligen. Het hoofdstuk concludeerde dat vaardigheid of blootstelling het priming-effect tussen twee talen (dat werd gevonden in hoofdstuk 3) niet beïnvloedde bij gesimuleerde simultaan tweetaligen, in lijn met wat werd gevonden bij menselijke deelnemers.

**Hoofdstuk 5** onderzocht of ERP's bij L2-leerders als reactie op syntactische overtredingen verklaard kunnen worden als impliciet leren. Er werd een versie van het Dual-path-model gebruikt, dat ontwikkeld was om gebeurtenisgerelateerde potentialen in monolinguale zinsverwerking te simuleren. In dit hoofdstuk werd dit model uitgebreid om ERP's in tweetalige zinsverwerking te simuleren. De resultaten toonden aan dat het model rekening kan houden met hoe ERP's zich ontwikkelen tijdens het leren als reactie op syntactische overtredingen bij het leren van een tweede taal. Daarnaast simuleerde het model ook de invloed van gelijkenis tussen talen op dergelijke ERP's. In tegenstelling tot menselijke deelnemers vertoonden gesimuleerde deelnemers echter een kleine P600-respons op genderovertredingen, die uniek waren voor de L2.

**Hoofdstuk 6** onderzocht of codeswitching en cross-language structurele priming een wisselwerking zouden kunnen hebben in het model en bij mensen. Het toonde ten eerste aan dat de structurele priming van actieve en passieve structuren van Spaans naar Engels toenam met codeswitching in de prime vergeleken met niet-codeswitched primes in het tweetalige dual-path model. Dit was alleen het geval als de codeswitch bestond uit een codeswitched lidwoord en zelfstandig naamwoord aan het begin van de zin, maar niet voor drie andere typen codeswitches. Ten tweede lieten de resultaten van een online priming-experiment zien dat het effect van codeswitching op cross-language structurele priming dat in het model werd gevonden, ook optrad bij Spaans-Engels tweetalige deelnemers. Dit toonde voor het eerst aan dat het tweetalige Dual-path model nieuwe experimentele resultaten succesvol kan voorspellen.

In dit proefschrift wordt tweetalige syntaxis onderzocht als foutgebaseerd impliciet leren. De resultaten laten zien dat een dergelijk leermechanisme, geïnstantieerd in het tweetalige dual-path-model, experimentele bevindingen over cross-language structurele priming en ERP's in L2-leren verklaart, en dat het model nieuwe experimentele resultaten kan voorspellen over hoe verwerking van code-switches structurele priming tussen twee talen beïnvloedt. Zo heeft het proefschrift ons begrip van een reeks tweetalige fenomenen die een centrale rol spelen in het psycholinguïstische onderzoek naar tweetalige syntaxis, verder vergroot door een plausibel onderliggend mechanisme te presenteren dat deze verklaart. Tegelijkertijd heeft het proefschrift gezorgd voor verdere validatie van dat mechanisme.

# Publications

## Journal papers

**Khoe, Y. H.**, Frank, S. (2024). The Bilingual Dual-path model: Simulating bilingual production, processing, and development. *Linguistic Approaches to Bilingualism*. https://doi.org/10.1075/lab.23072.kho

**Khoe, Y. H.**, Tsoukala, C., Kootstra, G.J., Frank, S. (2023). Is structural priming between different languages a learning effect? Modelling priming as error-driven implicit learning. *Language, Cognition and Neuroscience*, *38*, 537-557. https://doi.org/10.1177/0023830920911079

Hintz, F., **Khoe, Y. H.**, Strauß, A., Psomakas, A., Holler, J. (2023). Electrophysiological evidence for the enhancement of gesture-speech integration by linguistic predictability during multimodal discourse comprehension. *Cognitive, Affective, and Behavioral Neuroscience.*, *23*, 340–353. https://doi.org/10.3758/s13415-023-01074-8

Jongman, S.R., **Khoe, Y.H**., and Hintz, F. (2020). Vocabulary size influences spontaneous speech in native language users: Validating the use of automatic speech recognition in individual differences research. *Language and Speech*, *64*(1), 35-51. https://doi.org/10.1177/0023830920911079

### Registered reports

Hintz, F., Strauß, A., Conradi, S., **Khoe, Y. H.**, Holler, J. (2023, In-principle Acceptance). Language prediction in multimodal contexts: The contribution of iconic gestures to anticipatory sentence comprehension, *Cortex*, Stage 1 Registered Report. OSF Preprint: https://osf.io/679tm

### Conference papers

Verwijmeren, S., Frank, S.L., Fitz, H., **Khoe, Y. H.** (2024). Simulating event-related potentials in bilingual sentence comprehension: syntactic violations and syntactic transfer, *Proceedings of the 22nd International Conference on Cognitive Modeling (ICCM 2024). [PsyArXiv]*

Verwijmeren, S., Frank, S.L., Fitz, H., **Khoe, Y. H.** (2023). A neural network simulation of event-related potentials in response to syntactic violations in second-language learning, *Proceedings of the 21st International Conference on Cognitive Modeling (ICCM 2023). [Pdf]*

**Khoe, Y. H.**, Kootstra, G.J., Schoonen, R, Frank, S. (2021). Simulating the effect of proficiency or exposure on cross-language priming of transitives in simultaneous English-Spanish bilinguals, *Proceedings of the 19th International Conference on Cognitive Modeling (ICCM 2021)* (pp. 150-156).

**Khoe, Y. H.**, Tsoukala, C., Kootstra, G.J., Frank, S. (2020). Modeling cross-language structural priming in sentence production, *Proceedings of the 18th International Conference on Cognitive Modeling (ICCM 2020)* (pp. 131-137).

textbfKhoe, Y. H. (2020). Reproducing a morphosyntactic tagger with a Meta-BiLSTM model over context sensitive token encodings, *Proceedings of The 12th Language Resources and Evaluation Conference (LREC 2020)* (pp. 5565-5570).

**Khoe, Y. H.**, Perfors, A., and Hendrickson, A. T. (2019). Modeling individual performance in cross-situational word learning. In A.K. Goel, C.M. Seifert, and C. Freksa (Eds.), *Proceedings of the 41st Annual Conference of the Cognitive Science Society* (pp. 560-566).

## Author contributions

### Chapter 1 and 7

These chapters were written by Yung Han Khoe (YHK) and were revised by him based on feedback provided by Stefan Frank (SF), Gerrit Jan Kootstra (GJK), and Rob Schoonen (RS).

### Chapter 2

This chapter is based on the abstract and sections 1, 2, 3.1, 3.2 and 3.4 of:
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Is structural priming between different languages a learning effect? Modelling priming as error-driven implicit learning,
*Language, Cognition and Neuroscience*, 38, (pp. 537-557)

The study was designed and performed by YHK, in collaboration with and under supervision of SF, Chara Tsoukala (CT), GJK, and RS. The manuscript was written by YHK and was revised by him based on feedback provided by SF, CT, GJK, RS, and reviewers.

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*Linguistic Approaches to Bilingualism*.

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### Chapter 4

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### Chapter 5

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A neural network simulation of event-related potentials in response to syntactic violations in second-language learning.
*Proceedings of the 21st International Conference on Cognitive Modelling*

and on:
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Simulating event-related potentials in bilingual sentence comprehension: syntactic violations and syntactic transfer.
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## Chapter 6

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# About the author

Yung Han Khoe was born in 1974 in Eindhoven, The Netherlands. In 2017 he completed a Bachelor's degree in Spanish Language and Culture at the University of Amsterdam, with honor (cum laude). As a part of this Bachelor's program, he spent a semester at the Universidad Autonoma de Madrid (Spain). He continued with a Research Master's degree in Linguistics and Communication Sciences at Radboud University, in Nijmegen, which he obtained in 2020 with the greatest honor (summa cum laude). At the same time, he also pursued a Master's degree in Cognitive Science and Artificial Intelligence at Tilburg University, which he completed with honor (cum laude) in 2019. During these studies, he worked as teaching assistant at Radboud University and as an intern and student assistant at the Max Planck Institute for Psycholinguistics. He presented the research of his Master's studies in 2019 at the Annual Conference of the Cognitive Science Society (CogSci) in Montreal, Canada, and in 2020 at the International Conference on Cognitive Modeling (ICCM), online. In 2020 he started on the PhD project presented in this dissertation at the Centre for Language Studies (CLS) at Radboud University. He was part of the Graduate School for the Humanities, International Max Planck Research School (IMPRs), and the Cognitive and Developmental Aspects of Bilingualism and the Grammar and Cognition research groups. As part of his PhD, he taught (parts of) courses on language acquisition, programming, research best practices, and statistics, at the bachelor's and master's level and to fellow PhD candidates and academic staff. He served on the organizing committees of the IMPRS introduction days and the CLS Talks, and as the volunteer coordinator at CogSci 2024 in Rotterdam. During his PhD project, he conducted research at the University of Florida, on a grant from the Fulbright Commission The Netherlands. In 2022, he interupted his PhD project for six months to work as a junior policy officer at the Dutch Science Council (NWO). After finishing this dissertation he started working as a research fellow at the School of Psychology at the University of Birmingham (UK).

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