2025. Proc Ling Soc Amer 10(1). 5909. https://doi.org/10.3765/plsa.v10i1.5909.

A dynamic neural field model of asymmetric interference effects in code-switching

Alessandra Pintado-Urbanc*

Abstract.
During instances of code-switching, bilingual speakers rapidly transition between languages. Following a transition from one language to the other, a code-switched word can exhibit phonetic differences from the same word produced in a single-language context. Observation of such 'interference' effects (Grosjean 2012) depends on language dominance. Interference effects are reported when a speaker switches from their non-dominant language into their dominant language, as shown, for example, in measurements of voice onset time (VOT) from Spanish-English bilinguals (Olson 2013). We propose a neurocognitive model of such effects using Dynamic Field Theory (DFT). Interference arises from the interaction of separate language inputs into a single VOT planning field. Following principles from the inverse frequency effect (Ferreira 2003), the amplitudes of the two language inputs are modulated by the frequency of language use, deriving the asymmetry. A key assumption underlying this result is that bilinguals' speech representations interact in a shared phonetic space.

Keywords. phonetics; bilingualism; code-switching; Dynamic Field Theory

1. Introduction. Unlike a monolingual speaker, a bilingual speaker must be able to store the mental representations of two distinct language systems as well as have the ability to selectively activate either language depending on their communicative goals. When in a monolingual context, the competing language must be inhibited in order to successfully speak in the intended target language (Green 1998; Grosjean 2001; Olson 2024). Under this view, the language systems appear to be independent of each other and can be activated as determined by the goals and intentions of the speaker.

However, there are instances in which language systems *can* interact. Code-switching is one such instance. Code-switching refers to the ability of a bilingual speaker to quickly transition from one language to another during fluid speech (Myers-Scotton 1993). An example of code-switching is presented in (1). Here, the sentence begins in English, transitions to Spanish (bolded), and then transitions back to English.

(1) Hey, **vamos al** park today?
'Hey, should we go to the park today?'

Evidence from code-switching shows that when the languages are both activated, they can influence each other, as reflected in phonetic measurements. Following a transition from one language to the other, a code-switched word can exhibit phonetic differences from the same word produced in a monolingual context. While it is argued that the two phonetic systems are distinct (Olson 2024), they can still interact with each other and yield such 'interference' effects (Grosjean 2012).

* Thank you to the members of the Yale Dynamics Group for their insightful feedback and discussion. Any errors are my own. Alessandra Pintado-Urbanc, Yale University (alessandra.pintado-urbanc@yale.edu)

One way of accounting for such phonetic interaction is by assuming the existence of a common representational space for both language systems (Flege 1995). In this context, Dynamic Field Theory (DFT) (Schöner & Spencer 2016) provides a useful theoretical framework to represent the dynamic interaction between two independent languages systems in a common space. DFT uses dynamical systems to model neural activation and is particularly valuable as it can bridge the discrete and continuous representations of language. For example, phonemes, morphemes, and words are considered to be discrete units while articulator positions, voice onset times (VOT), and vowel formant values are continuous measurements. Discrete language categories may emerge through the modulation of continuous variables. For the case of a bilingual speaker, competing and discrete language inputs can interact in a single neural field causing gradient modulation of continuous variables. Crucially, these phonetic interference effects occur when both language inputs are sufficiently activated.

This paper presents a neurocognitive model using Dynamic Field Theory that accounts for asymmetric phonetic interference effects during code-switching. The paper is structured as follows: §2 will explore key concepts essential for understanding bilingualism and code-switching, §3 will review empirical data on phonetic interference in Spanish-English bilinguals (Olson 2013) and §4 will present the neurocognitive model and simulations that capture this phenomenon through the implementation of a single, shared space.

2. The Interaction of Multiple Language Systems. Previous work has shown that the language systems of a bilingual speaker can influence each other across varying time scales (e.g., short term versus long term) as well as in different forms (e.g., unidirectional versus bidirectional). Moreover, the language environments and experiences of speakers can also influence the way in which the language systems interact. The following sections will explore these factors and highlight their importance for the implementation of a DFT model that accounts for bilingual phonetic interference.

2.1. LANGUAGE TRANSFER VERSUS INTERFERENCE. The interaction between language systems can be characterized by its impact on either the *long-term* or *working* memory representations (Grosjean 2012). *Transfer* is a process of language influence which occurs on a longer time scale and subsequently affects the long-term memory representations. On the other hand, *interference* occurs on a short-term timescale and affects the working-memory representations. Both transfer and interference can be considered to be dynamic processes of change. However, a process of transfer unfolds over a longer time scale whereas interference describes a process where one language can influence another in real-time given a particular speech context.

These different forms of language interaction have both been supported by empirical data. When studying Spanish-Catalan bilingual speakers, Simonet (2011) provides evidence for a vowel merging effect of the Catalan vowels /o/ and /ɔ/ for Spanish dominant bilinguals. Here, the dominant language of Spanish has influenced the vowel representations and has dissolved the Catalan vowel contrast causing the vowel merger. This occurs because the vowel contrast between /o/ and /ɔ/ does not exist in the phonological inventory of Spanish. Thus, this vowel merging effect reflects a permanent change in the long-term vowel representation of these bilingual speakers and is an example of transfer.

However, Simonet (2014) presents a case of language interference with the same two vowel representations for Spanish-Catalan bilingual speakers. During instances where the language systems are both active, as in code-switching, Catalan dominant speakers, who otherwise maintain the contrast, produce the /ɔ/ more similarly to the Spanish /o/. This phonetic difference, however, does not impact the long-term memory representations as the Catalan speakers do not lose the vowel contrast between /o/ and /ɔ/.

Language transfer and interference describe ways in which language systems can be affected in either the long-term or short-term memory representations. However, language interaction can also differ in direction of interaction, regardless of whether it is a case of transfer or interference.

2.2. Unidirectional versus Bidirectional Interaction. Bilingual speakers are traditionally characterized as having a L1 (first language) and a later acquired L2 (second language). Crucially, previous empirical studies have revealed different patterns in the interaction between a speaker's L1 and L2 phonetic systems.

For example, the speaker's L1 can influence the productions of a later learned L2. Studies reported instances where the L2 productions appear to be more similar to the L1 during instances of code-switching (Antoniou et al. 2011; Balukas & Koops 2015; Bullock & Toribio 2009; Piccinini & Arvaniti 2015). Further, this influence is clear when observing the accented speech patterns of individuals who learn their L2 later in life (Flege 1995). There are also studies showing the opposite interaction: influence of the L2 on the L1 (Olson 2013). Moreover, there are reports of bidirectional influence where both language systems influence each other (Olson 2016; Tsui et al. 2019). Finally, there is also evidence that shows *no* interaction with neither the L1 nor the L2 influencing the resulting productions (Grosjean & Miller 1994; López 2012).

Given the variation of results from these studies, it is challenging to commit to one theory regarding the interaction between the L1 and L2 phonetic systems. One potential difference across these studies is the source of data. While some studies acquired the data through spontaneous and naturalistic productions (i.e., a naturalistic task, corpus data, etc.) (Balukas & Koops 2015; Piccinini & Arvaniti 2015), others have participants complete single word language switching tasks (Olson 2013), produce full code-switched sentences (Olson 2016; Bullock & Toribio 2009; Grosjean & Miller 1994), or perform a language switching task with nonce words (Antoniou et al. 2011). Thus, to some extent, the variation in results can be explained by the variation of tasks used. Another way to understand the disparity across these studies is by examining the role of language dominance profiles and language contexts. These two factors may be able to predict occurrences of language influence.

2.3. Language Modes and Language Dominance. *Language modes* refers to the degree to which a bilingual uses either language given particular intentions and social contexts (Grosjean & Miller 1994; Grosjean 1989). Rather than a categorical distinction of a speaker either being in a monolingual or bilingual communicative situation, language modes are conceived of as a scalar continuum from fully monolingual to bilingual speech. This language mode continuum can also be considered as modulations of the level of activation of either language given the context. Phonetic interactions would be more expected during language modes where both languages are activated, such as in code-switching, as opposed to instances of purely monolingual speech.

Language dominance can also impact the ways in which the phonetic systems interact. Bilingual speakers will typically have a 'dominant' and 'non-dominant' language. The dominant language is usually acquired first and used more frequently in school, work and other social settings. Moreover, speakers are typically less competent in their non-dominant language. While bilingual speakers can be proficient in both languages, a dominant language may have more regular linguistic input and increased competence.

The empirical data used to ground the neurocognitive model includes different language modes and language dominance profiles. We argue that, in particular, differences in language dominance and subsequently frequency of language use can predict how two language systems will interact.

3. Empirical Data: Olson (2013). The data used to ground the neurocognitive model stems from results in Olson (2013) that report phonetic interference effects in a language switching task. The experiment involved a 'cued picture-naming paradigm' in which Spanish-English bilingual participants produced the labels of pictures in different languages given previously learned color-to-language cues (e.g., the label of a picture with a blue background was produced in English while the label of one with a red background was produced in Spanish). Across experimental trials, the dependent variable of interest was voice onset time (VOT) for the voiceless velar stop /k/. Voice onset time refers to the time between the release of a consonant and the onset of voicing.

The experiment also aimed to investigate the influence of language modes on phonetic interference. To do so, they created two conditions: a monolingual condition (where 95% of the trials were in one language with 5% produced in the other) and a bilingual condition (where 50% of the trials were produced in either language). Each participant completed all three conditions: Monolingual English (95% of trials in English), Monolingual Spanish (95% of trials in Spanish) and Bilingual (50% of the trials in English and 50% in Spanish). For the purposes of the current paper, what is of interest are the monolingual trials. In order to examine the role of language dominance on phonetic interference there were two Spanish-English bilingual speaker groups: an English dominant group (with Spanish as their non-dominant language) and a Spanish dominant group (with English as their non-dominant language).

3.1. Spanish and English Voice Onset Time Differences. While both English and Spanish have voiced and voiceless stop consonants in their phonological systems, the phonetic characteristics of these stops differ cross-linguistically. For example, whereas voiceless stops, like /p/, /t/, and /k/, in English have long voice onset time (VOT) values (Lisker & Abramson 1964), in Spanish, these same phonemes have shorter positive VOT values (Abramson & Lisker 1973). These phonetic differences in VOT values between an English and Spanish voiceless consonant is also known as the 'long-lag' and 'short-lag' distinction. This difference follows for voiced stops like /b/, /d/, and /g/. English voiced stops have a 'short-lag' VOT, whereas Spanish voiced stops are pre-voiced with voicing beginning before the stop closure ('lead' voicing). Figure 1 presents a schematic of the difference between Spanish and English VOT distributions.

While the encoding of this cross-linguistic distinction is clear for monolingual speakers, a bilingual speaker must represent the distributions of voiced and voiceless consonants for both languages. Storing these representations in a unified system allows for the possibility of phonetic interaction when both languages are co-activated.

3.2. Asymmetric Interference Results. Olson (2013) recorded VOT values for two different trial types: (1) 'stay' trials in which the production language does not differ from that of the previous trial and (2) 'switch' trials in which the language of the current trial differs from the one used in the previous trial. They found that in the monolingual condition, there was evidence of language interference for 'switch' trials but only when switching from a speaker's non-dominant language to their dominant language. That is, when switching back into their dominant

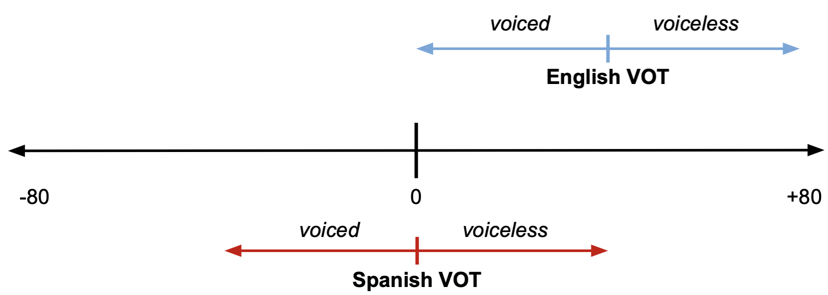


Figure 1. English and Spanish Voice Onset Time (adapted from Llama et al. (2010))

language, participants exhibited language interference effects from the previous non-dominant language trial. However, they did not exhibit this interference effect when switching from their dominant language to their non-dominant language. This asymmetric interference effect in the direction of the non-dominant language is present for both the English dominant and Spanish dominant speaker groups as shown in Tables 1 and 2 respectively. The data shows that there is a difference in VOT values between 'stay' and 'switch' trials for productions in a participant's dominant language (i.e., English for the English dominant group and Spanish for Spanish dominant group) but no difference between 'stay' and 'switch' VOT values for productions in the non-dominant language.

Trial Type	Previous Trial	Current Trial	M (msec)	SD (msec)	Significance
English Stay	English	English	79.43	20.7	†[1]
English Switch	Spanish	English	72.56	20.1	
Spanish Stay	Spanish	Spanish	37.88	17.1	ns
Spanish Switch	English	Spanish	37.46	15.5	

[1] Marginal significance (p = 0.08).

Table 1. VOT Values of /k/ for English Dominant Speakers by Trial Type (Olson 2013)

Trial Type	Previous Trial	Current Trial	M (msec)	SD (msec)	Significance
Spanish Stay	Spanish	Spanish	31.22	18.1	***
Spanish Switch	English	Spanish	39.05	16.3	
English Stay	English	English	73.47	21.6	ns
English Switch	Spanish	English	68.69	24.3	

Table 2. VOT Values of /k/ for Spanish Dominant Speakers by Trial Type (Olson 2013)

As shown in Table 1, the resulting mean English VOT value for the 'switch' trials is shorter and is more 'Spanish-like'. However, there is no interference effect in the opposite direction: for an English dominant speaker, the mean Spanish VOT value does not differ between 'stay' and ‘switch’ trials. Once again, the same asymmetric effect is observed for Spanish dominant speakers as shown in Table 2. Here, during ‘switch’ trials, the mean Spanish VOT measurement is more ‘English-like’ as it is longer than during ‘stay’ trials.

4. Modeling Asymmetric Interference Effects in Dynamic Field Theory. Whereas Dynamic Field Theory (DFT) has been used to model human motor control, memory representations, and developmental processes (Schöner & Spencer 2016), it has also recently been used in the field of linguistics to develop a unified account of the discrete and continuous representations of language. Recent studies have used this framework to examine phonetic trace effects during speech errors (Stern et al. 2022), contrastive hyper-articulation in speech planning (Stern & Shaw 2023), as well as effects of prosody in the representation of lexical items (Tang & Shaw 2021). For a more comprehensive overview of DFT, see Stern (2025) in these proceedings.

4.1. DYNAMIC FIELD THEORY. Under this framework, the activation of a population of neurons evolve over time in a Dynamic Neural Field (DNF) (Amari 1977). By varying field and input parameters, peaks in the DNF may stabilize at different rates and in different locations of a continuous feature field. The continuous feature of the current model is voice onset time (VOT). The activation over time in the VOT field is defined according to (1). In this equation, there are two inputs $s_{English}$(x,t) and $s_{Spanish}$(x,t) representing the two languages (English and Spanish) stored in a bilingual's mind.

$$\tau\dot{u}(x,t) = -u(x,t) + h + s_{English}(x,t) + s_{Spanish}(x,t) + \int k(x-x')g(u(x',t))dx' + q\xi(x,t) \quad (1)$$

This equation relates the rate of change of the activation of a population of neurons, $\dot{u}$(x,t), to *u*, the current activation. The rate of change is defined over *x*, the position within the continuous feature space (in this case VOT values) and over *t*, which represents time. In the model, the field size was set to 120 neurons to represent a field which spans from 0 to 120 ms of VOT values. τ represents a time constant which controls how fast the field evolves. Importantly, ‘h + $s_{English}$(x,t) + $s_{Spanish}$(x,t) + ∫ k(x-x’)g(u(x’,t))dx’ + qξ (x,t)’ represents the attractor within the dynamical system where *h* is the resting level (in this model, set to -5). Moreover, the model has two inputs, one English language VOT input as $s_{English}$(x,t) and one Spanish language VOT input as $s_{Spanish}$(x,t). These two language inputs have their own Gaussian distributions with their own parameters. Each input is defined by an amplitude *a*, a position in the field *p*, and a width of the Gaussian distribution *w*. The equation for the two language inputs is presented in (2).

$$s(x,t) = a\exp\left[-\frac{(x-p)^2}{2w^2}\right] \quad (2)$$

‘k(x-x’)’ represents the interaction kernel of the model. Once neurons pass an activation threshold, they affect the activation of other neurons in the field through this interaction kernel. The equation for this component of the model is in (3). Within this interaction kernel, there are both excitatory and inhibitory variables. Whereas c_{exc} and c_{inh} vary the local excitatory and inhibitory components respectively, c_{glob} refers to global inhibition across the entire field. Finally, σ_{exc} and σ_{inh} control the width of the excitatory and inhibitory distributions within the interaction kernel.

$$k(x-x') = \frac{c_{exc}}{\sqrt{2\pi}\sigma_{inh}}\exp\left[-\frac{(x-x')^2}{2\sigma_{exc}^2}\right] - \frac{c_{inh}}{\sqrt{2\pi}\sigma_{inh}}\exp\left[-\frac{(x-x')^2}{2\sigma_{inh}^2}\right] - c_{glob} \quad (3)$$

The $g(u)$ component of equation (1) represents the sigmodially gated activation threshold which is represented by the function in (4). The last component of the equation, qξ(x,t), represents random noise that is introduced into the system by a parameter q. This simulates real-world variation in the neural activity.

$$g(u) = \frac{1}{1 + \exp(-\beta u)} \tag{4}$$

The specific variable parameters used in the model discussed in this paper are provided in Table 3 below. These parameters allow for 'selection' within the system to ensure that the peak stabilizes at only one area within the VOT field rather than in multiple areas. This accounts for the fact that the language production system can only produce one VOT value at a time. The model was built in COSIVINA, a MATLAB software (Schneegans 2021).

Parameter	Value
τ	20
h	-5
β	4
c_{exc}	21
c_{inh}	0
c_{glob}	0.9
σ_{exc}	5
σ_{inh}	12.5
q	1

Table 3. Parameters for Dynamic Neural Field Model

4.2. ACCOUNTING FOR THE ASYMMETRY. One way to account for the asymmetric phonetic interference effect reported in Olson (2013) is by considering how the frequency of usage of either language can impact the occurrence of interference in code-switching. Recall, the participants in this experiment were not balanced bilinguals but rather were characterized as having a dominant language and a non-dominant language counterpart.

One way to consider the relative activation of both languages during a language switching task is by drawing on core principles from syntactic priming effects. The Inverse Frequency Effect (IFE) describes a phenomenon whereby less frequent syntactic structures have greater priming effects relative to more frequent structures (Jaeger & Snider 2007; Ferreira 2003). We propose that this can be extended to speech production in a language switching task. Here, there is an inverse relationship between the frequency of use of a language and the priming effect for the next production. That is to say, a less frequently used language (e.g., a non-dominant language) will have a greater priming effect for subsequent trials relative to a more frequent language. In this model, priming refers to the residual activation of the competitor language. Thus, for very frequent items (i.e., trials in a participant's dominant language), subsequent trials will have low residual priming and thus a smaller activation value of the competitor language. On the other hand, a trial in a participant's non-dominant language will be less frequent and thus will have greater priming and more residual activation during subsequent trials.

4.3. MODEL INPUT PARAMETERS. Following the data reported in Olson (2013), the mean VOT values of the English dominant and Spanish dominant participants were used as *p* values for the respective language inputs. For example, the reported mean VOT value for English 'stay' trials for an English dominant speaker was 79.43 ms. Thus, this was the value at which the Gaussian distribution of the English input was centered on the VOT field. For that same speaker group, during Spanish 'stay' trials, the reported mean VOT value was 37.88 ms. This was subsequently used as the *p* value for their Spanish VOT input. It should be noted that there are differences between the *p* values for the same language input for an English dominant versus Spanish dominant speaker. This is expected as, overall, an English dominant speaker will have longer VOT values while a Spanish dominant speaker will generally have shorter VOT values.

The *w* parameter, representing the width of the Gaussian distribution for both English and Spanish dominant speakers, was set to 21 ms. This value roughly represents the standard deviation of the mean VOT values. Table 4 presents the *p* and *w* values for the two language inputs for each participant group.

Input	Parameter	English Dominant	Spanish Dominant
$s_{dominant}$	*p*	79.43	73.47
	w	21	21
$s_{non-dominant}$	*p*	37.88	31.22
	w	21	21

Table 4. Input Position (*p*) and Width (*w*) Values for English and Spanish Inputs

In order to model the asymmetric phonetic interference effect in a bilingual language switching task, the amplitudes of the language inputs were modulated given different trial types. The amplitude values *a* for each trial type are presented in Table 5.

Trial Type	Dominant Input Value	Non-Dominant Input Value
Dominant Stay (dominant to dominant)	6	1
Non-Dominant Stay (non-dominant to non-dominant)	1	6
Dominant Switch (non-dominant to dominant)	4	3
Non-Dominant Switch (dominant to non-dominant)	1	5

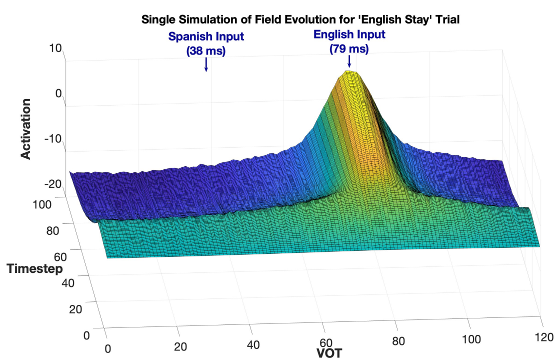
Table 5. Input Amplitude (a) Values

Previous work has claimed that even during monolingual contexts, bilingual speakers "minimally activate" the competing language (Marian et al. 2007; Marian & Spivey 2003). Thus, even for 'stay' trials, when a speaker does not switch into another language, the competitor language is still minimally activated with an input value of 1. However, the target language is fully activated to pass threshold with an input of 6. This is shown in Table 5 for the 'dominant stay' and 'non-dominant stay' trials where the target language has a value of 6 with the competitor language having a value of 1.

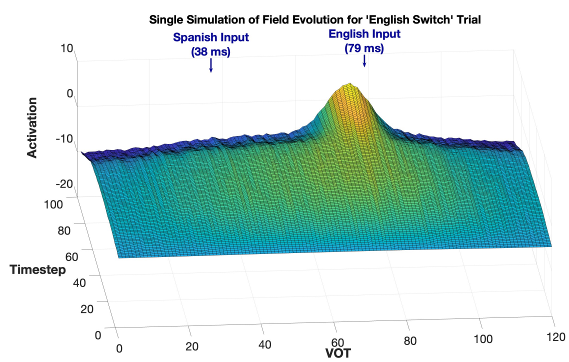
Crucially, to derive the asymmetry, the input values for the 'switch' trials differ based on whether the speaker was switching into their non-dominant or dominant language. When switching from their dominant language into their non-dominant language (as in a 'non-dominant switch' trial), there is little residual priming from the frequent dominant language. This follows from the discussion in §4.2 and principles from the inverse frequency effect. Thus, the dominant input value is set to 1 while the non-dominant input value is set to 5. The reason for a reduced activation value of ‘5’ follows from the Inhibitory Control Model (Green 1986, 1998) which claims that during language switching, the competitor language must be inhibited. During rapid language switching, there may be residual inhibition for subsequent trials. So, during a ‘non-dominant switch’ trial, there was inhibition of the non-dominant language in the previous dominant language production. Then, when switching into the non-dominant language, there is residual inhibition (in the form of decreased activation) causing the input value to be set to 5.

Describing the amplitude values of the language input in terms of a relationship between residual activation and residual inhibition allows us to explain the values for the ‘dominant switch’ trials where a speaker switches from their non-dominant language into their dominant language. Here, there is residual activation from the non-dominant language (leading to an input value of 3) as well as residual inhibition from the previous inhibited dominant language (during the non-dominant trial). Crucially, we assume that there is greater inhibition (in the form of less overall activation) given the differences in dominance profiles: the dominant language would be inhibited more during non-dominant productions.

4.4. MODEL SIMULATIONS. Following the model parameters described above, the ‘stay’ and ‘switch’ trials can be simulated in a DFT framework. Figure 2 presents the model simulations for English dominant speakers for the English ‘stay’ and ‘switch’ trials. As shown in Figure 2a, during the ‘stay’ trials, when the speaker produces two successive trials in English, there is no interference effect from Spanish. This is clear as the peak stabilizes at 79 ms at the 30th timestep. However, in ‘switch’ trials as shown in Figure 2b, due to the increased Spanish input activation, the peak in the field now stabilizes at 72 ms at the 79th timestep. The resulting VOT value is now more ‘Spanish-like’ as it was influenced by the activation of the competing non-dominant language.



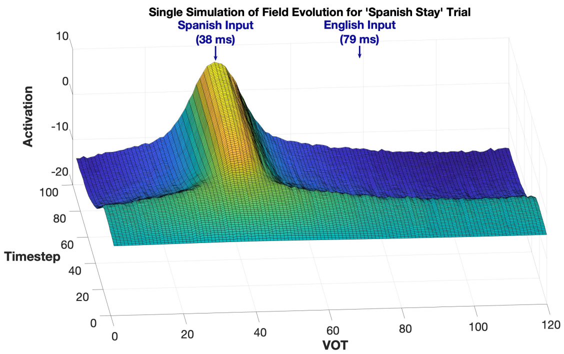
(a) English Stay Trial



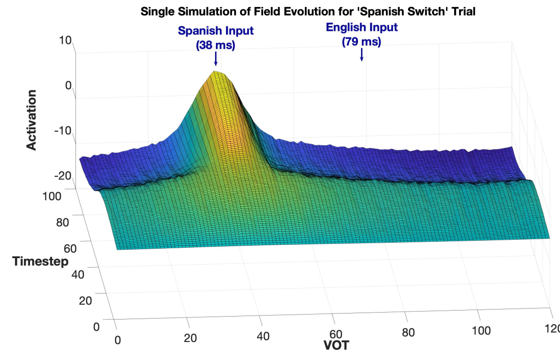
(b) English Switch Trial

Figure 2. Simulations of English Trials for English Dominant Speakers

However, as shown in Figures 3a and 3b, for the same English dominant speaker group, there is no interference effect for the Spanish ‘stay’ or ‘switch’ trials. This is clear as the peak stabilizes at around 38 ms for both trial types. That is to say, for a ‘switch’ trial, when a speaker switches from their dominant language into their non-dominant language, there is no influence from the competing dominant English input. This shows the asymmetric behavior of the interference effect.



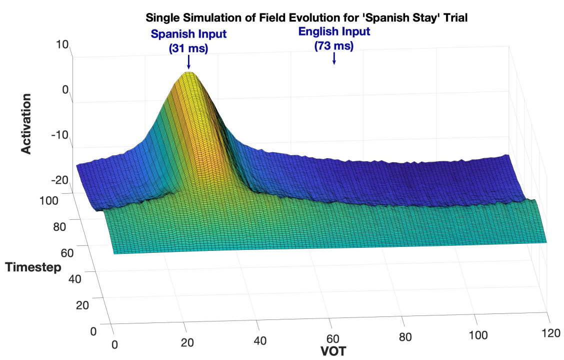
(a) Spanish Stay Trial



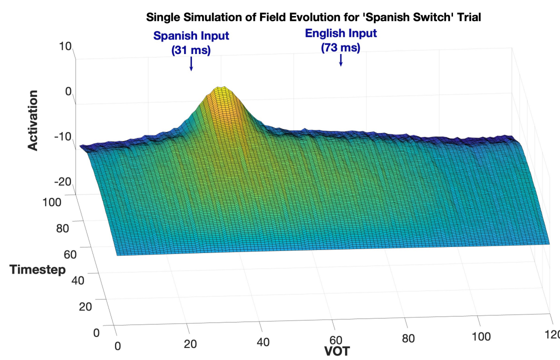
(b) Spanish Switch Trial

Figure 3. Simulations of Spanish Trials for English Dominant Speakers

Crucially, given that this phenomenon was not language specific, the model also accurately captures this effect for the Spanish dominant speaker group. As shown in Figure 4, there is no effect of the competing non-dominant English input in Spanish ‘stay’ trials but there is an effect in ‘switch’ trials. In this simulation, the peak now stabilizes at 39ms (Figure 4b) instead of 31ms (Figure 4a). Further, as shown in Figures 5a and 5b there is no interference effect for the English ‘stay’ and ‘switch’ trials, once again highlighting the asymmetry.



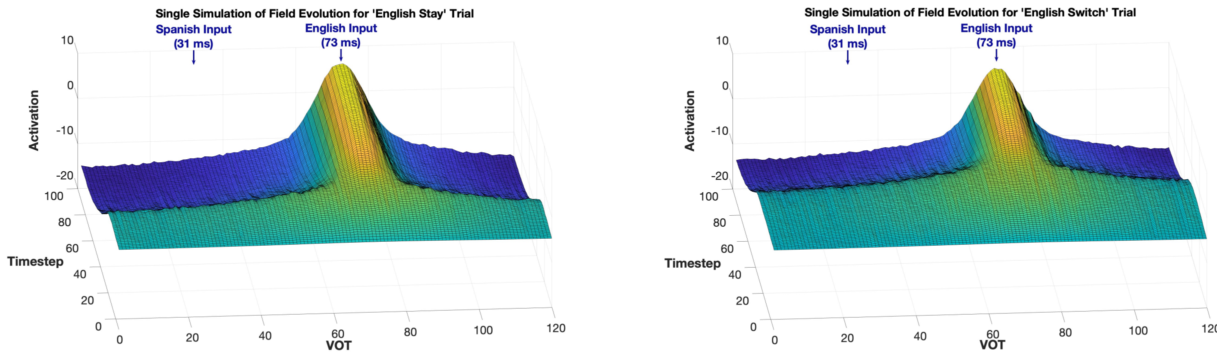
(a) Spanish Stay Trial



(b) Spanish Switch Trial

Figure 4. Simulations Simulations of Spanish Trials for Spanish Dominant Speakers

Furthermore, for both participant groups, in ‘dominant switch’ trials, the timestep at which the peak stabilizes occurs later as compared to ‘dominant stay’ trials. While Olson (2013) did not report reaction time values during this task, previous studies have shown a lexical ‘switch-cost’ in the form of reaction time when switching from the non-dominant language into the dominant language (Costa & Santesteban 2004; Meuter & Allport 1999). This increase in timestep at which the peak stabilizes correctly models a ‘switch-cost’ when switching from the non-dominant language into the dominant language. Thus, not only are there phonetic differences when switching from the non-dominant language into the dominant language but there may also be increased cognitive processing demands.



(a) English Stay Trial

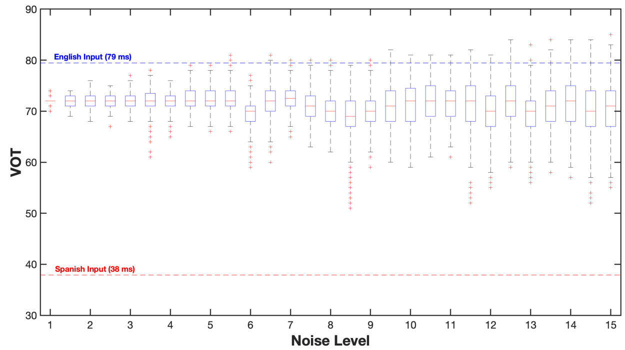
(b) English Switch Trial

Figure 5. Simulations of English Trials for Spanish Dominant Speakers

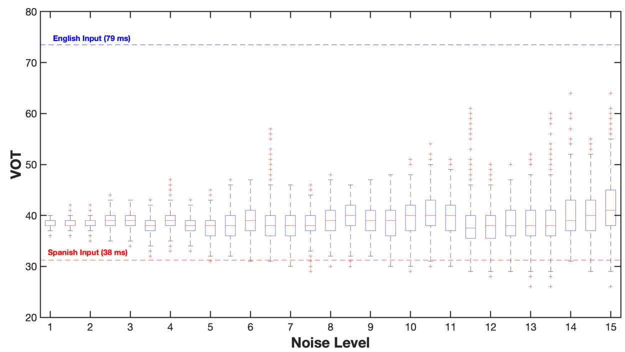
4.4.1. Examining the Effect of Increased Cognitive Load. This model can also be applied to examine how speech productions vary across different cognitive situations. For example, we can investigate how different levels of cognitive load can influence the reported phonetic interference effects. For instance, Piccinini & Arvaniti (2015) found that in a spontaneous Spanish-English code-switching task, VOT values were shorter for code-switched English words as compared to monolingual productions. However, when increasing the cognitive load for participants (adding a puzzle completion task during code-switching), they found that the VOT values were longer. That is, English VOT values were longer during code-switching with increased cognitive load but still shorter than during monolingual productions. This shows that these phonetic interference effects are diminished during cognitive situations with increased cognitive demands.

One way to model an increase in cognitive load is by increasing the level of noise within a VOT planning field. In particular, we investigated the role of noise across trials where participants switch from their non-dominant language into their dominant language. Following the methodology from Stern et al. (2022) the noise value (q) was varied from 1 to 15 in steps of 0.5. For each value, 500 simulations of field evolutions were run for 'dominant switch' trials. We measured the output VOT value for a single neuron with the highest activation in the field. Figure 6 shows the effect of noise on output VOT values for both English and Spanish dominant speaker groups. As shown in the figures, phonetic interference effects persist even with high levels of noise. The peak still stabilizes at intermediate values between the target and competing language inputs. However, the variance of the VOT outputs increases as noise increases.

Thus, given the simulation results, the model does not capture the effect of cognitive load as reported by Piccinini & Arvaniti (2015). Based on these findings, we would have expected that increasing noise would lead to differing VOT values – higher for English Dominant and lower for Spanish dominant – thus diminishing the phonetic interference effect. Crucially, while Figure 6 shows no effect on VOT value, it *does* show an increase in variance as noise level increases. This discrepancy may be partly attributed to the difference in number of tokens analyzed in Piccinini & Arvaniti (2015) as compared to the model's simulations (50 versus 500, respectively). A larger sample size may preserve the phonetic interference effect while increasing variance. Alternatively, it is possible that noise alone is not an adequate parameter to model cognitive load. Future research should evaluate whether other methods (e.g., changing input widths, input amplitudes, etc.) would be more suitable to capture this effect.



(a) English Dominant



(b) Spanish Dominant

Figure 6. Effects of VOT Values by Noise Level for 'Dominant Switch' Trial (q)

5. Discussion and Future Directions. By modulating language input amplitudes given different trial types and dominance profiles, this neurocognitive model is able to simulate the phonetic interference effect as reported by Olson (2013). Moreover, the model also makes novel predictions.

While Olson (2013) did not aim to measure reaction time, others have reported a 'switch-cost' when a speaker switches into their dominant language. The model predicts this 'switch-cost' as observed by the later time-steps at which the peak stabilizes. Further, the model also predicts there to be no interference effects for speakers of languages whose VOT distributions do not overlap. Recall that given the input positions p and widths w, the language input distributions overlap in the Dynamic Neural Field. This overlap allows for the interaction of the language inputs when sufficiently activated and subsequently accounts for the phonetic interference effects. However, we would not expect such interaction when inputs do not overlap (see Kramer & Shaw (2025) for an example of non-overlapping inputs in South Swedish). Thus, we would expect no phonetic interference during code-switching for a bilingual speaker that speaks two languages with non-overlapping VOT distributions. For example, such a case would be a bilingual speaker of Lebanese Arabic (a language with a very short VOT values for voiceless segments) and Thai (a language with very long VOT values for voiceless segments) (Cho et al. 2019).

The present model can also be extended to account for instances in which participants are exposed to equal levels of language input. For example, in the bilingual condition of Olson (2013), participants were exposed to trials of both languages equally. In these conditions, no asymmetric interference effects were found. Furthermore, other studies have shown that balanced bilinguals exhibit symmetrical interference effects (Tsui et al. 2019). The model could account for both reported effects by modulating the input amplitude values given frequency of language exposure and use. Further, if these effects are based on frequency of language usage, we may expect differences in reported VOT values over the course of the experiment with VOT values for 'dominant switch' trials being closer to the dominant language at the beginning of the experiment as opposed to the end.

It should also be noted that there are also ways in which the current architecture of the model could be expanded upon. In its current form, language systems are represented as the amplitude of inputs into the Dynamic Neural Field. However, the specific dynamics governing these input amplitudes are not specified. One extension could involved adding 'phoneme' or 'language' nodes that are coupled to this VOT planning field. When a speaker intends on producing a lexical item in a particular language, these nodes are activated and send input into the VOT planning field. Different choices regarding the structure of this architecture could yield different predictions. Future work should aim to develop models that more fully represent speech planning and production processes.

6. Conclusion. As shown by the model simulations, by using a Dynamic Field Theory framework, we are able to capture the asymmetric phonetic interference effects observed during the language switching of bilingual speakers. Crucially, a key assumption underlying this model is that bilinguals' speech representations interact in a shared phonetic space.

References

Abramson, Arthur S. & Leigh Lisker. 1973. Voice-timing perception in Spanish word-initial stops. *Journal of Phonetics* 1(1). 1–8. https://doi.org/10.1016/S0095-4470(19)31372-5.

Amari, Shun-ichi. 1977. Dynamics of pattern formation in lateral-inhibition type neural fields. *Biological Cybernetics* 27(2). 77–87. https://doi.org/10.1007/BF00337259.

Antoniou, Mark, Catherine T. Best, Michael D. Tyler & Christian Kroos. 2011. Inter-language interference in VOT production by L2-dominant bilinguals: Asymmetries in phonetic code-switching. *Journal of phonetics* 39(4). 558–570. https://doi.org/10.1016/j.wocn.2011.03.001.

Balukas, Colleen & Christian Koops. 2015. Spanish-English bilingual voice onset time in spontaneous code-switching. *International Journal of Bilingualism* 19(4). 423–443. https://doi.org/10.1177/1367006913516035. Publisher: SAGE Publications Ltd.

Bullock, Barbara E. & Almeida Jacqueline Toribio (eds.). 2009. *The Cambridge handbook of linguistic code-switching* The Cambridge handbook of linguistic code-switching. New York, NY, US: Cambridge University Press. https://doi.org/10.1017/CBO9780511576331.

Cho, Taehong, D. H. Whalen & Gerard Docherty. 2019. Voice onset time and beyond: Exploring laryngeal contrast in 19 languages. *Journal of Phonetics* 72. 52–65. https://doi.org/10.1016/j.wocn.2018.11.002.

Costa, Albert & Mikel Santesteban. 2004. Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language* 50(4). 491–511. https://doi.org/10.1016/j.jml.2004.02.002. Place: Netherlands Publisher: Elsevier Science.

Ferreira, Victor S. 2003. The processing basis of syntactic persistence: We repeat what we learn. In *44th Annual Meeting of the Psychonomic Society, Vancouver, Canada*, .

Flege, Jim. 1995. *Second language speech learning theory, findings and problems*, vol. In Strange, W. (Ed.), Speech perception and linguistic experience: Issues in crosslanguage research. Maryland: New York Press.

Green, David W. 1986. Control, activation, and resource: A framework and a model for the control of speech in bilinguals. *Brain and Language* 27(2). 210–223. https://doi.org/10.1016/0093-934X(86)90016-7. Place: Netherlands Publisher: Elsevier Science.

Green, David W. 1998. Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition* 1(2). 67–81. https://doi.org/10.1017/S1366728998000133. Place: United Kingdom Publisher: Cambridge University Press.

Grosjean, François. 1989. Neurolinguists, beware! The bilingual is not two monolinguals in one person. *Brain and Language* 36(1). 3–15. https://doi.org/10.1016/0093-934X(89)90048-5. Place: Netherlands Publisher: Elsevier Science.

Grosjean, François. 2001. The Bilingual's Language Modes. In *One mind, two languages: Bilingual language processing* Explaining linguistics, 1–22. Malden: Blackwell Publishing.

Grosjean, François. 2012. An attempt to isolate, and then differentiate, transfer and interference. *International Journal of Bilingualism* 16(1). 11–21. https://doi.org/10.1177/1367006911403210.

Grosjean, François & Joanne L. Miller. 1994. Going in and out of languages: An example of bilingual flexibility. *Psychological Science* 5(4). 201–206. https://doi.org/10.1111/j.1467-9280.1994.tb00501.x. Place: United Kingdom Publisher: Blackwell Publishing.

Jaeger, T Florian & Neal Snider. 2007. Implicit Learning and Syntactic Persistence: Surprisal and Cumulativity 3(1).

Kramer, Benjamin Matthew & Jason Shaw. 2025. Effects of Minimal Pair Competitors on Voice Onset Time and Pitch Accent Production in South Swedish. https://doi.org/10.2139/ssrn.5133838.

Lisker, Leigh & Arthur S. Abramson. 1964. A Cross-Language Study of Voicing in Initial Stops: Acoustical Measurements. *WORD* 20(3). 384–422. https://doi.org/10.1080/00437956.1964.11659830.

Llama, Raquel, Walcir Cardoso & Laura Collins. 2010. The influence of language distance and language status on the acquisition of L3 phonology. *International Journal of Multilingualism* 7(1). 39–57. https://doi.org/10.1080/14790710902972255. Publisher: Routledge _eprint: https://doi.org/10.1080/14790710902972255.

López, Lisa M. 2012. Assessing the Phonological Skills of Bilingual Children From Preschool Through Kindergarten: Developmental Progression and Cross-Language Transfer. *Journal of research in childhood education: JRCE* 26(4). 371–391. https://doi.org/10.1080/02568543.2012.711800.

Marian, Viorica, Henrike K. Blumenfeld & Margarita Kaushanskaya. 2007. The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing Language Profiles in Bilinguals and Multilinguals. *Journal of Speech, Language, and Hearing Research* 50(4). 940–967. https://doi.org/10.1044/1092-4388(2007/067). Publisher: American Speech-Language-Hearing Association.

Marian, Viorica & Michael Spivey. 2003. Bilingual and monolingual processing of competing lexical items. *Applied Psycholinguistics* 24(2). 173–193.

https://doi.org/10.1017/S0142716403000092. Place: United Kingdom Publisher: Cambridge University Press.

Meuter, Renata F. I. & Alan Allport. 1999. Bilingual Language Switching in Naming: Asymmetrical Costs of Language Selection. *Journal of Memory and Language* 40(1). 25–40. https://doi.org/10.1006/jmla.1998.2602.

Myers-Scotton, Carol. 1993. *Duelling Languages: Grammatical Structure in Code-Switching*. Oxford University Press.

Olson, Daniel. 2013. Bilingual language switching and selection at the phonetic level: Asymmetrical transfer in VOT production. *Journal of Phonetics* 41(6). 407–420. https://doi.org/10.1016/j.wocn.2013.07.005.

Olson, Daniel J. 2016. The role of code-switching and language context in bilingual phonetic transfer. *Journal of the International Phonetic Association* 46(3). 263–285. https://doi.org/10.1017/S0025100315000468.

Olson, Daniel J. 2024. Code-Switching and Language Mode Effects in the Phonetics and Phonology of Bilinguals. In Mark Amengual (ed.), *The Cambridge Handbook of Bilingual Phonetics and Phonology*, 677–698. Cambridge University Press 1st edn. https://doi.org/10.1017/9781009105767.031.

Piccinini, Page & Amalia Arvaniti. 2015. Voice onset time in Spanish–English spontaneous code-switching. *Journal of Phonetics* 52. 121–137. https://doi.org/10.1016/j.wocn.2015.07.004.

Schneegans, S. 2021. COSIVINA: A Matlab Toolbox to Compose, Simulate, and Visualize Neurodynamic Architectures (Version 1.4).

Schöner, Gregor & John Spencer. 2016. *Dynamic thinking: a primer on dynamic field theory* Oxford series in developmental cognitive neuroscience. Oxford ; New York: Oxford University Press.

Simonet, Miquel. 2011. Production of a Catalan-specific vowel contrast by early Spanish-Catalan bilinguals. *Phonetica* 68(1-2). 88–110. https://doi.org/10.1159/000328847.

Simonet, Miquel. 2014. Phonetic consequences of dynamic cross-linguistic interference in proficient bilinguals. *Journal of Phonetics* 43. 26–37. https://doi.org/10.1016/j.wocn.2014.01.004.

Stern, Michael C. 2025. Dynamic Field Theory unifies discrete and continuous aspects of linguistic representations. *Proceedings of the Linguistic Society of America* 10.

Stern, Michael C, Manasvi Chaturvedi & Jason A Shaw. 2022. A dynamic neural field model of phonetic trace effects in speech errors. *Proceedings of the Annual Meeting of the Cognitive Science Society* 44.

Stern, Michael C. & Jason A. Shaw. 2023. Neural inhibition during speech planning contributes to contrastive hyperarticulation. *Journal of Memory and Language* 132. 104443. https://doi.org/10.1016/j.jml.2023.104443.

Tang, Kevin & Jason A. Shaw. 2021. Prosody leaks into the memories of words. *Cognition* 210. https://doi.org/10.1016/j.cognition.2021.104601. Place: Netherlands Publisher: Elsevier Science.

Tsui, Rachel Ka-Ying, Xiuli Tong & Chuck Siu Ki Chan. 2019. Impact of language dominance on phonetic transfer in Cantonese–English bilingual language switching. *Applied Psycholinguistics* 40(1). 29–58. https://doi.org/10.1017/S0142716418000449.