Coronal stop production in bilinguals

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# Introduction

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# Background and motivation

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# Method

## Participants

The data include 42 participants from 3 populations: monolingual English speakers, monolingual Spanish speakers, and bilingual Spanish-English speakers. All participants were females between the ages of 18 and 23. The monolingual English speakers were recorded in English and the monolingual Spanish speakers were recorded in Spanish. The Spanish-English bilinguals were recorded in both of their languages.

**Monolingual English speakers.** The study includes 8 monolingual English speakers. They were undergraduate students at the University of Arizona, born and raised in the US Southwest. The English speakers were functionally monolingual, though they reported having taken introductory Spanish courses. They were not able to maintain a basic conversation in Spanish. All of the participants in this group reported English as their native language and verified not having been exposed to any other languages while growing up.

**Monolingual Spanish speakers.** The monolingual Spanish group comprised 8 speakers that were recruited from the *Universitat de les Illes Balears* campus community and were born and raised on the island of Majorca, Spain. They reported that, although they had studied some English in Spain, they were not able to maintain a basic conversation in this language. The participants of this group also speak Catalan. Importantly, there are no reported differences in the phonetic realization of voice timing between the Spanish and Catalan, nor are there place difference between the coronal stops.

**Bilingual speakers.** The English-Spanish bilinguals (n = 26) came from Southern Arizona and Northern Mexico. There are two samples from this population. The coronal dataset includes 17 speakers and the bilabial dataset includes 9 speakers. The Spanish-English bilinguals were undergraduate students at the University of Arizona in Tucson, Arizona. The bilinguals were brought up by Spanish-speaking families and were schooled mostly in English. They reported using English and Spanish daily, both in the classroom as well as with their friends and relatives.

## Metrics

F1/F2, voice onset time, relative intensity, center of gravity, standard deviation, skewness, kurtosis

## Procedure

Decide if we will present 3 separate experiments with 3 different methods sections.

## Statistical analyses

All analyses were conducted in R (R Core Team, 2019, version 4.1.3). We use Bayesian multilevel models fitted in Stan using brms (Bürkner, 2017, 2018, version 2.16.3). Bayesian Data Analysis (BDA) is an alternative to frequentist statistical analysis.[[1]](#footnote-25) For all models, the criterion was standardized, or converted to z-scores, in order to facilitate comparability between metrics. Continuous predictors were also standardized and categorical predictors were sum-to-zero coded. Thus for all models the intercept represents the outcome variable at the grand mean in standardized units. We used regularizing, weakly informative priors in all models (specifics below) with 4,000 iterations (2,000 warm-up) running on 16 processing cores. We quantify our uncertainty regarding a given effect by reporting point estimates derived from the posterior predictive distribution, including the 95% Highest Density Credible Intervals (HDI). Additionally, we assume a negligible effect size of ± 0.1 (Cohen, 1988, 2013; Kruschke, 2018) in order to establish a Region of Practical Equivalence (ROPE), for which we assess the proportion of the HDI that falls within this interval. Finally, we report the Maximum Probability of Effect (MPE), or the Probability of Direction, as the proportion of the posterior distribution that is of the median’s sign. We assume there to be compelling evidence for a given effect when the HDI of the posterior distribution does not contain 0 nor fall within the ROPE by a reasonable margin and the MPE is close to 1.

# Results

The results are divided into 3 subsections dealing with (1) monolingual data, (2) bilingual data, and (3) POA data. Each subsection presents the results of 6 metrics: VOT, relative intensity, center of gravity, kurtosis, standard deviation, and skewness. We report only relevant effects. Please see the supplementary materials (Appendices A-D) for complete model summaries.

## Experiment 1: Monolinguals

We modeled VOT and the burst metrics as a function of language (English, Spanish), phoneme (/d/, /t/), standardized F1 and F2, and item repetitions. The model used regularizing, weakly informative priors (Gelman, Simpson, & Betancourt, 2017; Vasishth et al., 2018). Specifically, all parameters were assumed to be distributed as normal with a standard deviation of 5, i.e., , . The standard deviation parameters for random effects and the model residual error (sigma) were truncated to exclude negative values. Figure 1 plots VOT and the burst metrics as a function of language (English, Spanish) and phoneme (/d/, /t/). For all plots the y-axis represents the outcome variable in standardized units. The x-axis indicates the language and voiced/voiceless pairs are represented by color.

![Figure 1: VOT and burst metrics of coronal stops (/d/, /t/) from monolingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.](data:application/pdf;base64,)

Figure 1: VOT and burst metrics of coronal stops (/d/, /t/) from monolingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.

**Voice-onset time.** English stops had higher VOT than Spanish stops (β = 0.660, HDI = [0.556, 0.763], ROPE = 0, MPE = 1) and the voiceless segments had higher VOT than the voiced segments (β = −0.617, HDI = [−0.697, −0.544], ROPE = 0, MPE = 1). We also find moderate evidence for an interaction between the two predictors (β = 0.108, HDI = [0.033, 0.180], ROPE = 0.406, MPE = 0.995). Specifically, the voicing difference between Spanish coronals was slightly larger than that of the English coronals. We compared the short-lag stops of each language, English /d/ and Spanish /t/, and found no evidence that the segments differed from each other (β = 0.085, HDI = [−0.181, 0.335], ROPE = 0.489, MPE = 0.745), as nearly half the HDI fell within the predetermined region of practical equivalence. The VOT data is plotted in the first panel of Figure 1. The complete model summary and the short-lag stop comparison are available in Table 2 and Figure 9 of the supplementary materials.

**Relative intensity.** The relative intensity data is plotted in the top middle panel of Figure 1. English and Spanish stops differed little with regard to relative intensity. The model provided no compelling evidence for a group effect (β = 0.026, HDI = [−0.171, 0.246], ROPE = 0.666, MPE = 0.602), nor for phoneme (β = −0.060, HDI = [−0.192, 0.055], ROPE = 0.742, MPE = 0.83) or F2 effects (β = −0.080, HDI = [−0.177, 0.015], ROPE = 0.676, MPE = 0.948). The height of the following vowel did appear to modulate relative intensity of the burst to some degree (β = −0.172, HDI = [−0.252, −0.085], ROPE = 0.026, MPE = 1), such that higher F1 values were associated with lower relative intensity. That being said, approximately 2.6% of the HDI fell within the region of practical equivalence. Finally, there was no evidence supporting a language × phoneme interaction (β = 0.025, HDI = [−0.094, 0.157], ROPE = 0.906, MPE = 0.657).

**Center of gravity.** The center of gravity (COG) data is plotted in the first row, third panel of Figure 1. English stops had a higher COG than Spanish stops (β = 0.687, HDI = [0.555, 0.810], ROPE = 0, MPE = 1), and, overall, voiceless segments had a higher COG than the voiced segments (β = −0.298, HDI = [−0.354, −0.244], ROPE = 0, MPE = 1), however, the two predictors interacted (β = 0.214, HDI = [0.157, 0.266], ROPE = 0, MPE = 1). The interaction was driven by a large COG difference between Spanish coronals (Spanish /d/ vs. Spanish /t/: β = −1.024, HDI = [−1.184, −0.868], ROPE = 0, MPE = 1) that was not present in the English coronals (English /d/ vs. English /t/: β = −0.169, HDI = [−0.327, −0.012], ROPE = 0.172, MPE = 0.983)). No other predictors had an effect on COG.

**Kurtosis.** The kurtosis data is plotted in the second row, first column of Figure 1. English stop bursts had lower kurtosis with regard to Spanish stop bursts (β = −0.646, HDI = [−0.755, −0.542], ROPE = 0, MPE = 1), and the voiced segments presumably had a higher kurtosis than the voiceless segments (β = 0.290, HDI = [0.221, 0.361], ROPE = 0, MPE = 1), though there was evidence of a language × phoneme interaction (β = −0.263, HDI = [−0.332, −0.195], ROPE = 0, MPE = 1). Specifically, kurtosis was higher in the voiced stop bursts of Spanish (Spanish /d/ vs. Spanish /t/: β = 1.106, HDI = [0.905, 1.292], ROPE = 0, MPE = 1), but there was no evidence of a voicing difference in the English data (English /d/ vs. English /t/: β = 0.054, HDI = [−0.149, 0.247], ROPE = 0.659, MPE = 0.712). Neither F1 (β = −0.027, HDI = [−0.067, 0.015], ROPE = 1, MPE = 0.903) nor F2 (β = 0.001, HDI = [−0.038, 0.043], ROPE = 1, MPE = 0.509) had any influence on kurtosis.

**Standard deviation.** With regard to standard deviation, we observe the same pattern found in the COG data (See third panel, first row and second panel, second row in Figure 1). That is, there was a difference between English and Spanish (β = 0.490, HDI = [0.343, 0.648], ROPE = 0, MPE = 1), as well as between phonemes (β = −0.282, HDI = [−0.355, −0.204], ROPE = 0, MPE = 1), though, again, there two predictors interacted (β = 0.210, HDI = [0.141, 0.293], ROPE = 0, MPE = 1). Specifically, there was only a voicing difference for Spanish (Spanish /d/ vs. Spanish /t/: β = −0.985, HDI = [−1.193, −0.772], ROPE = 0, MPE = 1), where we see lower standard deviation values in voiced stops. No such difference is observed between the English coronals (English /d/ vs. English /t/: β = −0.143, HDI = [−0.365, 0.066], ROPE = 0.335, MPE = 0.91). Height and frontedness of the following vowel had no effect on standard deviation in the stop burst (F1: β = −0.001, HDI = [−0.051, 0.051], ROPE = 1, MPE = 0.509; F2: β = 0.007, HDI = [−0.044, 0.061], ROPE = 1, MPE = 0.595).

**Skewness.** The analysis of skewness of the stop burst showed a similar pattern as the one observed in the analysis of kurtosis. If we compare the first and third panels (second row) of Figure 1, we observe a language effect (β = −0.665, HDI = [−0.774, −0.561], ROPE = 0, MPE = 1), such that Spanish stops show higher skewness values, as well a voicing effect (β = 0.290, HDI = [0.222, 0.362], ROPE = 0, MPE = 1), which is driven by a language × phoneme interaction (β = −0.221, HDI = [−0.292, −0.155], ROPE = 0, MPE = 1). Specifically, the Spanish voiced coronal had higher skewness of the burst than the voiceless counterpart (Spanish /d/ vs. Spanish /t/: β = 1.023, HDI = [0.827, 1.214], ROPE = 0, MPE = 1), and this difference is not present in the English data (English /d/ vs. English /t/: β = 0.139, HDI = [−0.049, 0.34], ROPE = 0.339, MPE = 0.92). Again, F1 and F2 did not affect skewness values in the burst (F1: β = −0.016, HDI = [−0.058, 0.022], ROPE = 1, MPE = 0.771; F2: β = −0.011, HDI = [−0.051, 0.030], ROPE = 1, MPE = 0.708).

![Figure 2: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of monolingual coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘group’ indicates between-language comparisons of different speakers.](data:application/pdf;base64,)

Figure 2: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of monolingual coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘group’ indicates between-language comparisons of different speakers.

**Interim discussion.**

General summary and patterns. VOT no surprise RI does nothing spectral moments relevant in spanish, nothing in english Skewness and kurtosis pattern similarly, as do COG and standard deviation.

## Experiment 2: Bilinguals

Model info here.

![Figure 3: VOT and burst metrics of coronal stops (/d/, /t/) from bilingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.](data:application/pdf;base64,)

Figure 3: VOT and burst metrics of coronal stops (/d/, /t/) from bilingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.

**Voice-onset time.**

(β = 0.523, HDI = [0.481, 0.566], ROPE = 0, MPE = 1)

(β = −0.633, HDI = [−0.738, −0.522], ROPE = 0, MPE = 1)

(β = 0.025, HDI = [−0.017, 0.067], ROPE = 1, MPE = 0.883)

(F1: β = 0.016, HDI = [−0.013, 0.049], ROPE = 1, MPE = 0.847; F2: β = −0.016, HDI = [−0.053, 0.020], ROPE = 1, MPE = 0.813).

(β = −0.219, HDI = [−0.45, −0.001], ROPE = 0.128, MPE = 0.971)

**Relative intensity.**

(β = 0.097, HDI = [0.030, 0.161], ROPE = 0.543, MPE = 0.997)

(β = −0.070, HDI = [−0.147, 0.011], ROPE = 0.787, MPE = 0.959)

(β = −0.224, HDI = [−0.303, −0.139], ROPE = 0, MPE = 1)

(β = −0.073, HDI = [−0.134, −0.014], ROPE = 0.821, MPE = 0.991)

(β = 0.002, HDI = [−0.066, 0.063], ROPE = 1, MPE = 0.512)

**Center of gravity.**

(β = 0.661, HDI = [0.631, 0.692], ROPE = 0, MPE = 1)

(β = −0.308, HDI = [−0.340, −0.270], ROPE = 0, MPE = 1)

(β = 0.096, HDI = [0.067, 0.126], ROPE = 0.62, MPE = 1)

(F1: β = 0.036, HDI = [−0.001, 0.074], ROPE = 1, MPE = 0.967; F2: β = −0.015, HDI = [−0.053, 0.022], ROPE = 1, MPE = 0.783).

(Spanish /d/ vs. Spanish /t/: β = −0.807, HDI = [−0.9, −0.71], ROPE = 0, MPE = 1)

(English /d/ vs. English /t/: β = −0.425, HDI = [−0.509, −0.335], ROPE = 0, MPE = 1)

**Kurtosis.**

(β = −0.635, HDI = [−0.668, −0.603], ROPE = 0, MPE = 1)

(β = 0.276, HDI = [0.237, 0.313], ROPE = 0, MPE = 1)

(β = −0.173, HDI = [−0.204, −0.143], ROPE = 0, MPE = 1)

(F1: β = −0.018, HDI = [−0.056, 0.022], ROPE = 1, MPE = 0.808; F2: β = −0.009, HDI = [−0.048, 0.029], ROPE = 1, MPE = 0.666).

(Spanish /d/ vs. Spanish /t/: β = 0.897, HDI = [0.798, 1.003], ROPE = 0, MPE = 1)

(English /d/ vs. English /t/: β = 0.207, HDI = [0.11, 0.3], ROPE = 0, MPE = 1)

**Standard deviation.**

(β = 0.568, HDI = [0.534, 0.604], ROPE = 0, MPE = 1)

(β = −0.230, HDI = [−0.282, −0.178], ROPE = 0, MPE = 1)

(β = 0.082, HDI = [0.046, 0.115], ROPE = 0.866, MPE = 1)

(F1: β = 0.000, HDI = [−0.043, 0.046], ROPE = 1, MPE = 0.506; F2: β = 0.004, HDI = [−0.038, 0.050], ROPE = 1, MPE = 0.571).

(Spanish /d/ vs. Spanish /t/: β = −0.625, HDI = [−0.754, −0.499], ROPE = 0, MPE = 1)

(English /d/ vs. English /t/: β = −0.296, HDI = [−0.417, −0.174], ROPE = 0, MPE = 1)

**Skewness.**

(β = −0.611, HDI = [−0.642, −0.576], ROPE = 0, MPE = 1)

(β = 0.298, HDI = [0.264, 0.337], ROPE = 0, MPE = 1)

(β = −0.140, HDI = [−0.169, −0.105], ROPE = 0, MPE = 1)

(F1: β = −0.029, HDI = [−0.068, 0.012], ROPE = 1, MPE = 0.921; F2: β = −0.008, HDI = [−0.047, 0.031], ROPE = 1, MPE = 0.649).

(Spanish /d/ vs. Spanish /t/: β = 0.875, HDI = [0.774, 0.978], ROPE = 0, MPE = 1)

(English /d/ vs. English /t/: β = 0.317, HDI = [0.221, 0.41], ROPE = 0, MPE = 1)

![Figure 4: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of bilingual coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘Language’ refers to a within-participant comparison between English and Spanish.](data:application/pdf;base64,)

Figure 4: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of bilingual coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘Language’ refers to a within-participant comparison between English and Spanish.

## Experiment 3: Bilingual POA data

Model info here.

![Figure 5: VOT and burst metrics of voiceless stops from bilingual speakers as a function of language (English, Spanish), place of articulation (Coronal, Bilabial). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.](data:application/pdf;base64,)

Figure 5: VOT and burst metrics of voiceless stops from bilingual speakers as a function of language (English, Spanish), place of articulation (Coronal, Bilabial). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 66% credible intervals.

**Voice-onset time.**

(β = 0.802, HDI = [0.750, 0.852], ROPE = 0, MPE = 1)

(β = 0.134, HDI = [0.029, 0.236], ROPE = 0.248, MPE = 0.992)

(β = 0.055, HDI = [0.004, 0.105], ROPE = 0.983, MPE = 0.984)

(F1: β = 0.013, HDI = [−0.025, 0.050], ROPE = 1, MPE = 0.751; F2: β = 0.000, HDI = [−0.046, 0.043], ROPE = 1, MPE = 0.505).

**Relative intensity.**

(β = 0.099, HDI = [0.042, 0.155], ROPE = 0.518, MPE = 1)

(β = −0.475, HDI = [−0.680, −0.269], ROPE = 0, MPE = 1)

(β = −0.003, HDI = [−0.056, 0.057], ROPE = 1, MPE = 0.542)

(β = −0.222, HDI = [−0.304, −0.136], ROPE = 0, MPE = 1)

(β = −0.059, HDI = [−0.116, −0.001], ROPE = 0.945, MPE = 0.978)

**Center of gravity.**

(β = 0.206, HDI = [0.177, 0.236], ROPE = 0, MPE = 1)

(β = 0.953, HDI = [0.862, 1.041], ROPE = 0, MPE = 1)

(β = 0.211, HDI = [0.181, 0.239], ROPE = 0, MPE = 1)

(F1: β = 0.019, HDI = [−0.008, 0.049], ROPE = 1, MPE = 0.905; F2: β = −0.010, HDI = [−0.041, 0.020], ROPE = 1, MPE = 0.743).

(Spanish /t/ vs. English /t/: β = 0.835, HDI = [0.781, 0.888], ROPE = 0, MPE = 1)

(Spanish /p/ vs. English /p/: β = −0.01, HDI = [−0.112, 0.093], ROPE = 0.976, MPE = 0.574)

**Kurtosis.**

(β = −0.204, HDI = [−0.237, −0.173], ROPE = 0, MPE = 1)

(β = −0.888, HDI = [−1.006, −0.774], ROPE = 0, MPE = 1)

(β = −0.169, HDI = [−0.200, −0.137], ROPE = 0, MPE = 1)

(F1: β = 0.015, HDI = [−0.016, 0.047], ROPE = 1, MPE = 0.831; F2: β = −0.015, HDI = [−0.047, 0.017], ROPE = 1, MPE = 0.822).

(Spanish /t/ vs. English /t/: β = −0.747, HDI = [−0.809, −0.692], ROPE = 0, MPE = 1)

(Spanish /p/ vs. English /p/: β = −0.071, HDI = [−0.186, 0.039], ROPE = 0.696, MPE = 0.891)

**Standard deviation.**

(β = 0.230, HDI = [0.186, 0.271], ROPE = 0, MPE = 1)

(β = 0.766, HDI = [0.671, 0.870], ROPE = 0, MPE = 1)

(β = 0.209, HDI = [0.169, 0.250], ROPE = 0, MPE = 1)

(F1: β = −0.012, HDI = [−0.050, 0.030], ROPE = 1, MPE = 0.725; F2: β = 0.008, HDI = [−0.035, 0.049], ROPE = 1, MPE = 0.662).

(Spanish /t/ vs. English /t/: β = 0.876, HDI = [0.802, 0.951], ROPE = 0, MPE = 1)

(Spanish /p/ vs. English /p/: β = 0.042, HDI = [−0.107, 0.187], ROPE = 0.783, MPE = 0.722)

**Skewness.**

(β = −0.222, HDI = [−0.255, −0.188], ROPE = 0, MPE = 1)

(β = −0.888, HDI = [−0.994, −0.781], ROPE = 0, MPE = 1)

(β = −0.192, HDI = [−0.226, −0.159], ROPE = 0, MPE = 1)

(F1: β = −0.024, HDI = [−0.058, 0.009], ROPE = 1, MPE = 0.924; F2: β = 0.009, HDI = [−0.025, 0.042], ROPE = 1, MPE = 0.696).

(Spanish /t/ vs. English /t/: β = −0.829, HDI = [−0.889, −0.765], ROPE = 0, MPE = 1)

(Spanish /p/ vs. English /p/: β = −0.061, HDI = [−0.176, 0.06], ROPE = 0.748, MPE = 0.845)

![Figure 6: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of bilingual voiceless bilabial and coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘Place’ refers to a between-participants comparison, as the bilabial data comes from a separate group of bilingual individuals.](data:application/pdf;base64,)

Figure 6: Posterior medians ±95% and 66% credible intervals for VOT and burst metrics of bilingual voiceless bilabial and coronal stops. Individual point shapes and colors represent the six metrics analyzed. In this analysis, ‘Place’ refers to a between-participants comparison, as the bilabial data comes from a separate group of bilingual individuals.

**Interim discussion.**

Figure 6

# Discussion

## Summary of findings

## Interpretation and implications

# Conclusion

## Experiment 0: Vowels

Prior to the stop analyses we scrutinized the formant structure, F1 and F2, of the vowel following the coronal stops. The purpose of this analysis was to determine if the low /a/ and /æ/ vowels of Spanish and English, respectively, differed from each other. This analysis was taken as a precautionary measure with the objective of determining whether or not coarticulation effects may be present in the stop metrics due to the possible different spectral envelopes of the next segment.

The F1 and F2 data were analyzed using separate Bayesian multilevel models. The criterion (F1 or F2) were standardized and modeled as a function of language (English, Spanish), phoneme (/d/, /t/), and item repetition. Language and phoneme were sum coded (-1, 1). The random effects structure included by-subject intercepts with random slopes for phoneme and item repetition, as well as by-item intercepts with a random slope for item repetition. The model included weakly informative priors with the mean centered at 0 and a standard deviation of 2.

The model suggested weak evidence for a language effect on F1 (β = 0.008, HDI = [−0.221, 0.203], ROPE = 0.693, MPE = 0.536) and F2 (β = 0.222, HDI = [−0.007, 0.462], ROPE = 0.121, MPE = 0.967). Together, the point estimates suggest the spectral centroid of the Spanish vowel was slightly higher and more posterior with respect to that of the English vowel. There was no evidence for a phoneme effect on F1 (β = 0.124, HDI = [0.007, 0.235], ROPE = 0.328, MPE = 0.981), nor on F2 (β = 0.129, HDI = [−0.042, 0.318], ROPE = 0.353, MPE = 0.917). Given the possibility of a small effect of language on the spectral envelope, standardized F1 and F2 were used in subsequent analyses of the coronal stops to control for any coarticulatory effects on the burst. Figure 7 plots the F1 × F2 data and Figure 8 plots the model summary. A complete summary of the F1 and F2 models is available in Table 1.

![Figure 7: F1 × F2 of /a/ from monolingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 80% credible intervals.](data:application/pdf;base64,)

Figure 7: F1 × F2 of /a/ from monolingual speakers as a function of language (English, Spanish). Transparent points represent raw data. Solid points indicate posterior means ± 95% and 80% credible intervals.

![Figure 8: Posterior medians ± 95% and 66% credible intervals for F1 and F2 from monolingual speaker data.](data:application/pdf;base64,)

Figure 8: Posterior medians ± 95% and 66% credible intervals for F1 and F2 from monolingual speaker data.

Table 1: Model summary for F1 and F2 as a function of language (English, Spanish), phoneme (/d/, /t/), and item repetition for monolingual data. The percentage of the HDI contained within the ROPE is based on an effect size of ±0.1.

| Metric | Parameter | Estimate | HDI | ROPE | MPE |
| --- | --- | --- | --- | --- | --- |
| F1 | Intercept | −0.031 | [−0.283, 0.205] | 0.587 | 0.606 |
|  | Language | 0.008 | [−0.221, 0.203] | 0.693 | 0.536 |
|  | Phoneme | 0.124 | [0.007, 0.235] | 0.328 | 0.981 |
|  | Item rep. | 0.018 | [−0.050, 0.089] | 1.000 | 0.689 |
|  | Language:Phoneme | 0.015 | [−0.097, 0.134] | 0.951 | 0.595 |
| F2 | Intercept | −0.060 | [−0.289, 0.198] | 0.563 | 0.692 |
|  | Language | 0.222 | [−0.007, 0.462] | 0.121 | 0.967 |
|  | Phoneme | 0.129 | [−0.042, 0.318] | 0.353 | 0.917 |
|  | Item rep. | 0.030 | [−0.045, 0.099] | 1.000 | 0.802 |
|  | Language:Phoneme | 0.015 | [−0.172, 0.194] | 0.757 | 0.566 |

Table 2: Model summary for VOT and burst metrics as a function of language (English, Spanish), phoneme (/d/, /t/), F1, F2, and item repetition for monolingual coronal stops. The percentage of the HDI contained within the ROPE is based on an effect size of ± 0.1.

| Metric | Parameter | Estimate | HDI | ROPE | MPE |
| --- | --- | --- | --- | --- | --- |
| VOT | Intercept | 0.010 | [−0.106, 0.133] | 0.943 | 0.566 |
|  | Group | 0.660 | [0.556, 0.763] | 0.000 | 1.000 |
|  | Phoneme | −0.617 | [−0.697, −0.544] | 0.000 | 1.000 |
|  | F1 | −0.010 | [−0.041, 0.020] | 1.000 | 0.752 |
|  | F2 | 0.010 | [−0.023, 0.042] | 1.000 | 0.730 |
|  | Item rep. | −0.014 | [−0.045, 0.018] | 1.000 | 0.806 |
|  | Group:Phoneme | 0.108 | [0.033, 0.180] | 0.406 | 0.995 |
| COG | Intercept | 0.048 | [−0.104, 0.185] | 0.775 | 0.746 |
|  | Group | 0.687 | [0.555, 0.810] | 0.000 | 1.000 |
|  | Phoneme | −0.298 | [−0.354, −0.244] | 0.000 | 1.000 |
|  | F1 | 0.005 | [−0.033, 0.044] | 1.000 | 0.590 |
|  | F2 | 0.008 | [−0.028, 0.050] | 1.000 | 0.653 |
|  | Item rep. | −0.031 | [−0.071, 0.008] | 1.000 | 0.934 |
|  | Group:Phoneme | 0.214 | [0.157, 0.266] | 0.000 | 1.000 |
| KT | Intercept | −0.026 | [−0.163, 0.109] | 0.864 | 0.640 |
|  | Group | −0.646 | [−0.755, −0.542] | 0.000 | 1.000 |
|  | Phoneme | 0.290 | [0.221, 0.361] | 0.000 | 1.000 |
|  | F1 | −0.027 | [−0.067, 0.015] | 1.000 | 0.903 |
|  | F2 | 0.001 | [−0.038, 0.043] | 1.000 | 0.509 |
|  | Item rep. | 0.019 | [−0.021, 0.062] | 1.000 | 0.809 |
|  | Group:Phoneme | −0.263 | [−0.332, −0.195] | 0.000 | 1.000 |
| RI | Intercept | −0.111 | [−0.347, 0.141] | 0.446 | 0.820 |
|  | Group | 0.026 | [−0.171, 0.246] | 0.666 | 0.602 |
|  | Phoneme | −0.060 | [−0.192, 0.055] | 0.742 | 0.830 |
|  | F1 | −0.172 | [−0.252, −0.085] | 0.026 | 1.000 |
|  | F2 | −0.080 | [−0.177, 0.015] | 0.676 | 0.948 |
|  | Item rep. | 0.051 | [−0.023, 0.131] | 0.916 | 0.912 |
|  | Group:Phoneme | 0.025 | [−0.094, 0.157] | 0.906 | 0.657 |
| SD | Intercept | 0.039 | [−0.148, 0.213] | 0.717 | 0.661 |
|  | Group | 0.490 | [0.343, 0.648] | 0.000 | 1.000 |
|  | Phoneme | −0.282 | [−0.355, −0.204] | 0.000 | 1.000 |
|  | F1 | −0.001 | [−0.051, 0.051] | 1.000 | 0.509 |
|  | F2 | 0.007 | [−0.044, 0.061] | 1.000 | 0.595 |
|  | Item rep. | −0.027 | [−0.077, 0.027] | 1.000 | 0.833 |
|  | Group:Phoneme | 0.210 | [0.141, 0.293] | 0.000 | 1.000 |
| SK | Intercept | −0.052 | [−0.187, 0.084] | 0.777 | 0.780 |
|  | Group | −0.665 | [−0.774, −0.561] | 0.000 | 1.000 |
|  | Phoneme | 0.290 | [0.222, 0.362] | 0.000 | 1.000 |
|  | F1 | −0.016 | [−0.058, 0.022] | 1.000 | 0.771 |
|  | F2 | −0.011 | [−0.051, 0.030] | 1.000 | 0.708 |
|  | Item rep. | 0.032 | [−0.009, 0.075] | 1.000 | 0.933 |
|  | Group:Phoneme | −0.221 | [−0.292, −0.155] | 0.000 | 1.000 |

![Figure 9: Posterior distribution comparing the short-lag stops, English /d/ and Spanish /t/. The white point represents the posterior mean ± 95% HDI and the grey region represents the ROPE (± 0.1).](data:application/pdf;base64,)

Figure 9: Posterior distribution comparing the short-lag stops, English /d/ and Spanish /t/. The white point represents the posterior mean ± 95% HDI and the grey region represents the ROPE (± 0.1).

Table 3: Model summary for VOT and burst metrics as a function of language (English, Spanish), phoneme (/d/, /t/), F1, F2, and item repetition for bilingual coronal stops. The percentage of the HDI contained within the ROPE is based on an effect size of ± 0.1.

| Metric | Parameter | Estimate | HDI | ROPE | MPE |
| --- | --- | --- | --- | --- | --- |
| VOT | Intercept | −0.075 | [−0.209, 0.059] | 0.647 | 0.863 |
|  | Language | 0.523 | [0.481, 0.566] | 0.000 | 1.000 |
|  | Phoneme | −0.633 | [−0.738, −0.522] | 0.000 | 1.000 |
|  | F1 | 0.016 | [−0.013, 0.049] | 1.000 | 0.847 |
|  | F2 | −0.016 | [−0.053, 0.020] | 1.000 | 0.813 |
|  | Item rep. | −0.009 | [−0.038, 0.019] | 1.000 | 0.728 |
|  | Language:Phoneme | 0.025 | [−0.017, 0.067] | 1.000 | 0.883 |
| COG | Intercept | −0.130 | [−0.248, −0.003] | 0.318 | 0.984 |
|  | Language | 0.661 | [0.631, 0.692] | 0.000 | 1.000 |
|  | Phoneme | −0.308 | [−0.340, −0.270] | 0.000 | 1.000 |
|  | F1 | 0.036 | [−0.001, 0.074] | 1.000 | 0.967 |
|  | F2 | −0.015 | [−0.053, 0.022] | 1.000 | 0.783 |
|  | Item rep. | 0.012 | [−0.023, 0.049] | 1.000 | 0.746 |
|  | Language:Phoneme | 0.096 | [0.067, 0.126] | 0.620 | 1.000 |
| KT | Intercept | 0.162 | [0.047, 0.291] | 0.128 | 0.994 |
|  | Language | −0.635 | [−0.668, −0.603] | 0.000 | 1.000 |
|  | Phoneme | 0.276 | [0.237, 0.313] | 0.000 | 1.000 |
|  | F1 | −0.018 | [−0.056, 0.022] | 1.000 | 0.808 |
|  | F2 | −0.009 | [−0.048, 0.029] | 1.000 | 0.666 |
|  | Item rep. | −0.028 | [−0.064, 0.010] | 1.000 | 0.936 |
|  | Language:Phoneme | −0.173 | [−0.204, −0.143] | 0.000 | 1.000 |
| RI | Intercept | −0.020 | [−0.217, 0.170] | 0.711 | 0.582 |
|  | Language | 0.097 | [0.030, 0.161] | 0.543 | 0.997 |
|  | Phoneme | −0.070 | [−0.147, 0.011] | 0.787 | 0.959 |
|  | F1 | −0.224 | [−0.303, −0.139] | 0.000 | 1.000 |
|  | F2 | −0.073 | [−0.134, −0.014] | 0.821 | 0.991 |
|  | Item rep. | 0.005 | [−0.039, 0.053] | 1.000 | 0.587 |
|  | Language:Phoneme | 0.002 | [−0.066, 0.063] | 1.000 | 0.512 |
| SD | Intercept | −0.111 | [−0.240, 0.022] | 0.426 | 0.951 |
|  | Language | 0.568 | [0.534, 0.604] | 0.000 | 1.000 |
|  | Phoneme | −0.230 | [−0.282, −0.178] | 0.000 | 1.000 |
|  | F1 | 0.000 | [−0.043, 0.046] | 1.000 | 0.506 |
|  | F2 | 0.004 | [−0.038, 0.050] | 1.000 | 0.571 |
|  | Item rep. | 0.014 | [−0.024, 0.056] | 1.000 | 0.750 |
|  | Language:Phoneme | 0.082 | [0.046, 0.115] | 0.866 | 1.000 |
| SK | Intercept | 0.116 | [−0.014, 0.253] | 0.403 | 0.959 |
|  | Language | −0.611 | [−0.642, −0.576] | 0.000 | 1.000 |
|  | Phoneme | 0.298 | [0.264, 0.337] | 0.000 | 1.000 |
|  | F1 | −0.029 | [−0.068, 0.012] | 1.000 | 0.921 |
|  | F2 | −0.008 | [−0.047, 0.031] | 1.000 | 0.649 |
|  | Item rep. | −0.008 | [−0.046, 0.029] | 1.000 | 0.664 |
|  | Language:Phoneme | −0.140 | [−0.169, −0.105] | 0.000 | 1.000 |

Table 4: Model summary for VOT and burst metrics as a function of language (English, Spanish), place of articulation (bilabial, coronal), F1, F2, and item repetition for bilingual voiceless stops. The percentage of the HDI contained within the ROPE is based on an effect size of ± 0.1.

| Metric | Parameter | Estimate | HDI | ROPE | MPE |
| --- | --- | --- | --- | --- | --- |
| VOT | Intercept | −0.086 | [−0.200, 0.027] | 0.601 | 0.928 |
|  | Language | 0.802 | [0.750, 0.852] | 0.000 | 1.000 |
|  | Place | 0.134 | [0.029, 0.236] | 0.248 | 0.992 |
|  | F1 | 0.013 | [−0.025, 0.050] | 1.000 | 0.751 |
|  | F2 | 0.000 | [−0.046, 0.043] | 1.000 | 0.505 |
|  | Item rep. | −0.003 | [−0.042, 0.034] | 1.000 | 0.567 |
|  | Language:Place | 0.055 | [0.004, 0.105] | 0.983 | 0.984 |
| COG | Intercept | −0.569 | [−0.665, −0.475] | 0.000 | 1.000 |
|  | Language | 0.206 | [0.177, 0.236] | 0.000 | 1.000 |
|  | Place | 0.953 | [0.862, 1.041] | 0.000 | 1.000 |
|  | F1 | 0.019 | [−0.008, 0.049] | 1.000 | 0.905 |
|  | F2 | −0.010 | [−0.041, 0.020] | 1.000 | 0.743 |
|  | Item rep. | 0.007 | [−0.026, 0.039] | 1.000 | 0.659 |
|  | Language:Place | 0.211 | [0.181, 0.239] | 0.000 | 1.000 |
| KT | Intercept | 0.571 | [0.428, 0.690] | 0.000 | 1.000 |
|  | Language | −0.204 | [−0.237, −0.173] | 0.000 | 1.000 |
|  | Place | −0.888 | [−1.006, −0.774] | 0.000 | 1.000 |
|  | F1 | 0.015 | [−0.016, 0.047] | 1.000 | 0.831 |
|  | F2 | −0.015 | [−0.047, 0.017] | 1.000 | 0.822 |
|  | Item rep. | −0.028 | [−0.065, 0.011] | 1.000 | 0.930 |
|  | Language:Place | −0.169 | [−0.200, −0.137] | 0.000 | 1.000 |
| RI | Intercept | 0.232 | [0.013, 0.434] | 0.091 | 0.983 |
|  | Language | 0.099 | [0.042, 0.155] | 0.518 | 1.000 |
|  | Place | −0.475 | [−0.680, −0.269] | 0.000 | 1.000 |
|  | F1 | −0.222 | [−0.304, −0.136] | 0.000 | 1.000 |
|  | F2 | −0.059 | [−0.116, −0.001] | 0.945 | 0.978 |
|  | Item rep. | 0.028 | [−0.049, 0.103] | 0.995 | 0.780 |
|  | Language:Place | −0.003 | [−0.056, 0.057] | 1.000 | 0.542 |
| SD | Intercept | −0.476 | [−0.594, −0.356] | 0.000 | 1.000 |
|  | Language | 0.230 | [0.186, 0.271] | 0.000 | 1.000 |
|  | Place | 0.766 | [0.671, 0.870] | 0.000 | 1.000 |
|  | F1 | −0.012 | [−0.050, 0.030] | 1.000 | 0.725 |
|  | F2 | 0.008 | [−0.035, 0.049] | 1.000 | 0.662 |
|  | Item rep. | 0.016 | [−0.033, 0.061] | 1.000 | 0.748 |
|  | Language:Place | 0.209 | [0.169, 0.250] | 0.000 | 1.000 |
| SK | Intercept | 0.527 | [0.410, 0.656] | 0.000 | 1.000 |
|  | Language | −0.222 | [−0.255, −0.188] | 0.000 | 1.000 |
|  | Place | −0.888 | [−0.994, −0.781] | 0.000 | 1.000 |
|  | F1 | −0.024 | [−0.058, 0.009] | 1.000 | 0.924 |
|  | F2 | 0.009 | [−0.025, 0.042] | 1.000 | 0.696 |
|  | Item rep. | 0.000 | [−0.037, 0.039] | 1.000 | 0.518 |
|  | Language:Place | −0.192 | [−0.226, −0.159] | 0.000 | 1.000 |

## Bayesian data analysis

This study employs Bayesian Data Analysis for quantitative inferential statistics. Specifically, this implies that we use Bayesian *credible intervals*—and other metrics—to draw statistical inferences. A Bayesian model calculates a posterior distribution, i.e., a distribution of plausible parameter values, given the data, a data-generating model, and any prior information we have about those parameter values. Posterior distributions are computationally costly. For this reason, we use the Hamiltonian Markov Chain Monte Carlo algorithm to obtain a sample that incldues thousands of values from the posterior distribution. In practical terms, what this means is that we do not calculate a single point estimate for an effect β, but rather we draw a sample of 4,000 plausible values for β. This allows us to quantify our uncertainty regarding β by summarizing the distribution of those values. We will use 4 statistics to describe the posterior distribution: (1) the mean, (2) the highest density credible interval (HDI), (3) the proportion of the HDI that falls within a Region of Practical Equivalence (ROPE), and (4) the Maximum Probability of Effect (MPE). The mean provides a point estimate for the distribution. The 95% highest density credible interval provides bounds for the effect. The ROPE designates a region of practical equivalence for a negligible effect and calculates the proportion of the HDI that falls within this interval.[[2]](#footnote-45) The MPE calculates the proportion of the posterior distribution that is of the median’s sign (or the probability that the effect is positive or negative).

If, for instance, a hypothesis states that β > 0, we judge there to be *compelling evidence* for this hypothesis if the mean point estimate is a positive number, if the 95% credible interval of β does not contain 0 and is outside the ROPE by a reasonably clear margin, and the posterior *P*(β > 0) is close to one. Together these four statistics allow us to quantify our uncertainty and provide an intuitive interpretation of any given effect. Consider a case in which the posterior mean of β is 100 and the 95% credible interval is [40, 160]. The interval tells us that we can be 95% certain the *true* value of β is between 40 and 160, given the data, our model, and our prior information. Furthermore, the interval allows us to specify areas of uncertainty. In this example, we can conclude that the effect is almost certain to be positive. The lower interval value of 40 tells us that 95% of the plausible values are greater than 40. We also note that the interval covers a wide range of values, thus we also conclude that we are not very certain about the size of the effect. This type of interpretation is not possible under a frequentist paradigm.

## About this document

This document was written in RMarkdown using papaja (Aust & Barth, 2018) and serves as a project report for our research group. The document is written as if it were the results section of a future manuscript. This implies that it is written in a way that allows it to be copy and pasted into the actual manuscript once it is available.

## Session info

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1. See Schoot & Depaoli (2014) and Vasishth, Nicenboim, Beckman, Li, & Kong (2018) for tutorials and in depth explanations related to BDA in the psychological and speech sciences. [↑](#footnote-ref-25)
2. We utilize a ROPE of ± 1 for standardized values. For non-standardized values Kruschke (2018) recommends using the formula in (1) [↑](#footnote-ref-45)