Supplementary Material II: Statistical Report of Time Course Analyses

using NHTS of Mixed Effects Modeling

Chapter 1: Mixed Effects Logistic Regression

Each trial in our experimental design has categorical responses, and we have multiple repeated measures, including Time, POA and Pronunciation. Thus, we used mixed effects modeling logistic regression to analyze the data.

1. **Model Construction**

Our data have a standard 2*2 **within-subject** design and we measured responses over **time**, which give rise to correlated data for repeated measures: each subject was repeatedly measured at different time points under different experimental conditions (POA & Pronunciation).

Unlike the growth curve analysis where we could aggregate over all the items to reduce the random effects to conduct a by subject analysis (and vise versa) (see Chapter 2 of this supplementary material), in logistic regressions we have to consider the random effects for both *Subject* and *Item* in the **same** model. In this model, we are examining the probability of a certain subject i (i=1…N) looking at the target at a certain time point j (j=1…J) when processing the item k, (k=1…K) at a specific pronunciation condition l (l = 0 & 1).

In addition to that, Place of Articulation is not a fully crossed factor by item in our design, because a certain item (e.g dog) cannot be either coronal or noncoronal.

Therefore, we took all the above-mentioned features into account when construct the statistical model for our data. Using mixed effects logistic regressions (Frizmaurice, Lard & Ward, 2001), we have constructed the completely full model (i.e. the model that fully describes the structure of our data):

For subject i at time j when processing item k,

Level 1:

$Log(Pr(Y_{ik}=1)/1- Pr(Y_{ik}=1))=$

$a_{0ik}+a_{1ik}Time_j+a_{2ik}POA_k+a_{3ik}Pronunciation_l+a_{4ik}Pronunciation_l*POA_k+a_{5ik}Time_j*POA_k+a_{6ik}Time_j*Pronunciation_l$
$+a_{7ik}*Time_j*POA_k*Pronunciation_l+\varepsilon_{ik}$

Level 2: We then do regressions for all the coefficients in level 1

$a_{0ik}=\beta_0+v_{0i}+u_{0k}$

This is the regression for the intercept coefficient. β_0 is the intercept for the fixed effects, v_{0i} is the random intercept for subject, and u_{0k} is the random intercept for item.

$a_{1ik}=\beta_1+v_{1i}+u_{1k}$

This is the slope coefficient for $Time_i$. β_1 is the slope of the fixed effects for Time, v_{1i} is the random slope of Time for subject and v_{ik} is the random slope of Time for item.

$a_{2ik}=\beta_2+v_{2i}$

This is the slope coefficient for POA_k. β_2 is the intercept for the fixed effects of POA, v_{2i} is the random slope of POA for subject. (**Note** that we do not have the random slope for item here. This is because the POA for a specific item k (e.g. dog), is already fixed. It cannot vary between coronal and noncoronal).

$a_{3ik}=\beta_3+v_{3i}+u_{3ik}$

This is the slope coefficient for Pronunciation_l. β_3 is the slope for the fixed effect of Pronunciations. v_{3i} is the random slope for subject and v_{3k} is the random slope for item. Like Time_j, Pronunciation is a repeated measure for each subject and each item.)

$a_{4ik}=\beta_4+v_{4i}$

This is the coefficient for Pronunciation_l * POA_k interaction. For the same reason as $a_{2i}=\beta_2+v_{2i}$, we do not have a random coefficient for item here.

$a_{5ik}=\beta_5+v_{5i}$

This is the coefficient for Time_j * POA_k interaction. β_5 is the slope for the fixed effect for this interaction. We also do not have a random coefficient for item here.

$a_{6ik}=\beta_6+v_{6i}+u_{6k}$

This is the coefficient for Time_j*Pronunciation_l interaction. β_6 is the coefficient for the fixed effect of this interaction. It is a very important coefficient for our model because we need to see whether subjects are differentiating correct and mispronunciations over time. v_{6i} is the random slope for subject and v_{6k} is the random slope for item.

$a_{7ik}=\beta_7+v_{7i}$

This is the coefficient for the three way interaction. β_7 is the coefficient for the fixed effect of this interaction. It **is the most important coefficient** for our scientific question, because we need to see whether subjects are differentiating correct pronunciation and mispronunciation for different POA over time. Similarly, we do not have a random coefficient for item here.

Plugging in level 2 to level 1, we have a complete full model as follows:

$$\text{Log}(\Pr(Y_{ij}=1)/1-\Pr(Y_{ij}=1))= (\beta_0+v_{0i}+u_{0k})+(\beta_1+v_{1i}+u_{1k})\text{Time}_j+(\beta_2+v_{2i})\text{POA}_k+(\beta_3+v_{3i}+u_{3k})\text{Pronunciation}_l+(\beta_4+v_{4i})\text{Pronunciation}_l*\text{POA}_k+(\beta_5+v_{5i})\text{Time}_j*\text{POA}_k+(\beta_6+v_{6i}+u_{6k})\text{Time}_j*\text{Pronunciation}_l+(\beta_7+v_{7i})*\text{Time}_j*\text{POA}_k*\text{Pronunciation}_l+\varepsilon_{ik}$$

To understand our model from a different perspective, we can rearrange the model:

$$\text{Log}(\Pr(Y_{ik}=1)/1-\Pr(Y_{ik}=1))= (\beta_0+\beta_1\text{Time}_{ik}+\beta_2\text{POA}_k+\beta_3\text{Pronunciation}_l+\beta_4\text{Pronunciation}_l*\text{POA}_k+\beta_5\text{Time}_j*\text{POA}_k+\beta_6\text{Time}_j*\text{Pronunciation}_l+\beta_7\text{Time}_j*\text{POA}_k*\text{Pronunciation}_l)+ (v_{0i}+v_{1i}\text{Time}_j+v_{2i}\text{POA}_k+v_{3i}\text{Pronunciation}_l+v_{4i}\text{Pronunciation}_l*\text{POA}_k+v_{5i}\text{Time}_j*\text{POA}_k+v_{6i}\text{Time}_j*\text{Pronunciation}_l+v_{7i}\text{Time}_j*\text{POA}_k*\text{Pronunciation}_l)+(u_{0k}+u_{1k}\text{Time}_j+u_{3k}\text{Pronunciation}_l+u_{6k}\text{Pronunciation}_l*\text{Time}_j)\varepsilon_{ik},$$

The coefficients in first parenthesis on the right side of the equation are the fixed effects; and the coefficients in second parenthesis are the random effects for subject. The coefficients in the third parenthesis are the random effects for item. The last item ε_{ik} is the random error term to indicate measurement noise that cannot be explained by subject or by item variations.

II. Parameter Estimation

Now we estimate the parameters of the model using maximum likelihood estimation (MLE). This step is achieved using the SAS software. This is because in other software like the lme4 package in R, there is no option to specify the variance-covariance structure for the random effects. Now let's run the full model in SAS by specifying the compound symmetry variance-covariance structure for the random effects.

```
/*LOAD THE DATA*/
libname libref "Desktop";
proc import datafile="desktop\all.csv" out=long dbms=csv replace;
    getnames=yes;
```

```
run;
/* view the dataset*/
proc print data=long;
run;

/*Full model with random intercepts and slopes for all repeated measures and interactions*/
PROC GLIMMIX DATA=long NOCLPRINT;
CLASS SubjID Item;
MODEL  Success = POA Pronunciation Time POA*Pronunciation POA*Time Pronunciation*Time
Pronunciation*POA*Time/SOLUTION DIST=BINARY LINK=LOGIT;
RANDOM INTERCEPT POA Pronunciation Time POA*Pronunciation POA*Time Pronunciation*Time
Pronunciation*POA*Time /SUBJECT=SubjID TYPE=VC;
RANDOM INTERCEPT Pronunciation Time Pronunciation*Time /SUBJECT=Item TYPE=VC;
RUN;
```

TYPE=**VS** in the SAS code specifies the diagonal structure of the variance-covariance matrix. Let's see the results:

```
NOTE: The GLIMMIX procedure is modeling the probability that Success='0'.
NOTE: Convergence criterion (PCONV=1.11022E-8) satisfied.
NOTE: PROCEDURE GLIMMIX used (Total process time):
      real time           3:19.02
      cpu time            3:18.70
```

Here are the results for the fixed effects for each of the five experiments in the paper (we did not print out the random effects as they are not relevant to our research question and we have a lot of random effects).

1. **Statistical Results of Experiment 1a: Infant Onset**

```
NOTE: The GLIMMIX procedure is modeling the probability that Success='0'.
NOTE: Convergence criterion (PCONV=1.11022E-8) satisfied.
NOTE: PROCEDURE GLIMMIX used (Total process time):
      real time           5.71 seconds
      cpu time            5.54 seconds
```

Experiment 1a: Fixed Effects for the full time window (Frame 13-100)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	0.9998	0.3739	12	2.67	0.0203
POA	-0.4409	0.5563	21	-0.79	0.4369
Pronunciation	0.2710	0.5958	10	0.45	0.6589
Time	-0.01798	0.007863	4	-2.29	0.0841
POA*Pronunciation	-0.3525	0.8275	21	-0.43	0.6745
POA*Time	0.005685	0.01144	21	0.50	0.6243
Pronunciation*Time	-0.02048	0.01574	6	-1.30	0.2409
POA*Pronunciation*Time	0.009541	0.02219	13	0.43	0.6742

The three-way interaction is not significant. However, we also did not find a significant effect for Pronunciation and Time interaction. To further examine this result, we analyzed the time window for frame 7 to 57 (33.33 msec each time frame). This time window is selected because we leave out the first 7 frames to allow the participant to make a saccade. We cut the time window after 1060m because by this time, the participants had achieved the maximal lexical activation in all the four conditions. Now we examine the results for the limited time window:

Experiment 1a: Fixed Effects for frame 7 to 57					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	1.7464	0.4957	12	3.52	0.0042
POA	-0.7127	0.7231	21	-0.99	0.3356
Pronunciation	0.3499	0.7823	10	0.45	0.6642
Time	-0.05139	0.01561	4	-3.29	0.0301
POA*Pronunciation	-0.2823	1.0313	21	-0.27	0.7870
POA*Time	0.01607	0.02199	21	0.73	0.4730
Pronunciation*Time	-0.02734	0.03230	6	-0.85	0.4297
POA*Pronunciati*Time	-0.00002	0.04340	13	-0.00	0.9996

We found a significant effect for time, indicating that participants are looking at the target object over time. However, we still failed to find a significant interaction between time and pronunciation. Unlike the prediction of underspecification, the three way interaction is not significant either for this critical time window. Therefore, for Experiment 1a, infant onset mispronunciation, we did not find evidence for underspecification.

2. **Statistical Results of Experiment 1b: Infant Coda**

```
NOTE: The GLIMMIX procedure is modeling the probability that Success='0'.
NOTE: Convergence criterion (PCONV=1.11022E-8) satisfied.
NOTE: PROCEDURE GLIMMIX used (Total process time):
      real time           27.03 seconds
      cpu time            25.92 seconds
```

Experiment 1b:Fixed Effects for the Full Time Window (Frame 13-100)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	0.7820	0.2697	12	2.90	0.0133
POA	0.3556	0.3758	27	0.95	0.3525
Pronunciation	0.1558	0.4150	12	0.38	0.7139
Time	0.005864	0.01143	16	0.51	0.6149
POA*Pronunciation	-0.4001	0.6363	27	-0.63	0.5347
POA*Time	-0.03743	0.01265	25	-2.96	0.0067
Pronunciation*Time	0.005953	0.02098	8	0.28	0.7838
POA*Pronunciati*Time	0.01012	0.02973	17	0.34	0.7377

The three way interaction is not significant. However, we did not find a significant effect for Pronunciation and Time interaction. To further examine this result, following the practice of Experiment 1a, we further analyzed the time window for frame when word activation occurred, i.e. frame 7 to 52. Results are shown below:

Experiment 1b: Fixed Effects, frame 7-52					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	1.2303	0.5334	12	2.31	0.0397
POA	1.4308	0.7457	27	1.92	0.0656
Pronunciation	2.4242	0.9206	12	2.63	0.0218
Time	-0.03545	0.01741	16	-2.04	0.0586
POA*Pronunciation	-2.6151	1.4757	27	-1.77	0.0877
POA*Time	-0.04039	0.02384	25	-1.69	0.1027

Pronunciation*Time	-0.05110	0.03568	8	-1.43	0.1899
POA*Pronunciation*Time	0.02951	0.05822	17	0.51	0.6187

A significant effect of Time is found for this time window when word activation occurred, suggesting that participants changed their fixation to the target object over time. We also found a marginally significant effect for the interaction of time and pronunciation, suggesting that participants differentiated between the correct and the mispronounced words over time. However, consistent with our previous analyses, the three-way interaction is not significant, suggesting that participants' fixation to target object was not contingent upon the place of articulation of the word labels of the target object.

3. Statistical Results of Experiment 2a: Adult Onset with Salient Phase Included

We conduct the analyses for the full time window with frame 1 to frame 100 (1667ms) using the same SAS code. Results for the fixed effects are shown below:

Experiment 2a: Fixed Effects for the Full Time Window (Frame 13-100)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	1.6509	0.2024	31	8.16	<.0001
POA	0.1910	0.1677	31	1.14	0.2634
Pronunciation	-0.3156	0.1657	31	-1.90	0.0661
Time	-0.02275	0.003971	31	-5.73	<.0001
POA*Pronunciation	-0.1777	0.2265	31	-0.78	0.4387
POA*Time	-0.00459	0.003284	31	-1.40	0.1722
Pronunciation*Time	-0.00246	0.003966	31	-0.62	0.5388
POA*Pronunciati*Time	0.006842	0.004107	23	1.67	0.1093

Like Experiment 1, the three-way interaction is not significant. Also, we did not find a significant effect for Pronunciation and Time interaction. To further examine this result, following the practice of Experiment 1, we further analyzed the time window for frame 13-61 when word activation occurred in this experiment.

Experiment 2a: Fixed Effects for Time Window 13-61					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	1.6903	0.4099	31	4.12	0.0003
POA	0.1572	0.4146	31	0.38	0.7070
Pronunciation	0.4059	0.3502	31	1.16	0.2554
Time	-0.02963	0.01115	31	-2.66	0.0123
POA*Pronunciation	-0.5592	0.4742	31	-1.18	0.2473
POA*Time	-0.00162	0.01021	31	-0.16	0.8753
Pronunciation*Time	-0.02738	0.01053	31	-2.60	0.0142
POA*Pronunciation*Time	0.01330	0.01239	23	1.07	0.2945

The results are similar as Experiment 1b. Over time, participants significantly differentiated correct pronunciations and mispronunciations. However, the coefficients for Time * POA * Pronunciation suggests that the effect of mispronunciation does not differ for different place of articulation conditions over time. Such results are consistent with our previous analyses.

4. Statistical Results of Experiment 2b: Adult Coda

Using the same model, we analyzed the adult coda data. As previously, we first analyzed the full time course, i.e. the first 100 frame (1667ms). Results for the fixed effects are shown below:

Experiment 2b: Fixed Effects for the full time window (Frame 13-100)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	2.5614	0.3193	29	8.02	<.0001
POA	0.4025	0.3640	29	1.11	0.2779
Pronunciation	0.7020	0.3446	29	2.04	0.0508
Time	-0.03760	0.005128	29	-7.33	<.0001
POA*Pronunciation	-0.2889	0.4616	29	-0.63	0.5363
POA*Time	-0.00151	0.006515	29	-0.23	0.8184
Pronunciation*Time	-0.03264	0.007776	29	-4.20	0.0002
POA*Pronunciati*Time	0.01006	0.009991	21	1.01	0.3256

Like the previously reported experiments, the three way interaction is not significant. Like Experiment 1b, we also found a significant effect for Pronunciation and Time interaction. Therefore, our findings for the full time frame of the coda experiment did not support underspecification. As not until frame 100 did subjects achieve the maximal fixation for all conditions in this experiment, no further time window is analyzed.

5. Statistical Results of Experiment 3: Adult Onset with Carrier Phase Removed

Experiment 3 Adult Onset (Time 13-100)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	1.8733	0.2747	24	6.82	<.0001
POA	0.1453	0.1857	24	0.78	0.4415
Pronunciation	0.1274	0.2296	24	0.55	0.5841
Time	-0.03066	0.006256	24	-4.90	<.0001
POA*Pronunciation	-0.1917	0.1833	24	-1.05	0.3060
POA*Time	0.000726	0.003609	24	0.20	0.8423
Pronunciation*Time	-0.01946	0.006212	24	-3.13	0.0045
POA*Pronunciation*Time	0.003302	0.004582	16	0.72	0.4815

With the entire 100 frames (i.e. 1667ms) included, we found a significant effect for Pronunciation over time, as suggested by Pronunciation * interaction, indicating that our data are valid because subjects were performing the task. Also, similar as previous experiments and the Bayesian analyses, there is no significant three-way interaction.

Now we follow the previous practice and limit the time window to the time frames where lexical activation occurred in this experiment:

Experiment 3 Fixed Effects (Time 13-64)					
Effect	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Intercept	2.3061	0.5062	24	4.56	0.0001
POA	-0.2701	0.5247	24	-0.51	0.6115
Pronunciation	0.7665	0.3557	24	2.15	0.0414
Time	-0.04826	0.01086	24	-4.44	0.0002
POA*Pronunciation	0.3781	0.4382	24	0.86	0.3968
POA*Time	0.01294	0.01204	24	1.08	0.2930
Pronunciation*Time	-0.04085	0.009879	24	-4.13	0.0004
POA*Pronunciati*Time	-0.01294	0.01221	16	-1.06	0.3049

The results are similar as before. Over time, participants significantly differentiated correct pronunciations and mispronunciations. However, if we look at the coefficients for Time * POA * Pronunciation, we will be able to see that the effect of mispronunciation does not differ for different place of articulation conditions over time.

6. Conclusion

We found that Significant effect for pronunciation over time but no three-way interaction for the time frame when word activation occurs. Thus, similar as our results from Bayesian Model Comparison, findings using Logistic Mixed Effects modeling at least suggested that for our data, the psycholinguistic prediction for underspecification does not hold true.