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Underspecification in Toddlers' and Adults' Lexical Representations

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Abstract

Recent research has shown that toddlers' lexical representations are phonologically detailed, quantitatively much like those of adults. Studies in this article explore whether toddlers' and adults' lexical representations are *qualitatively* similar. Psycholinguistic claims (Lahiri & Marslen-Wilson, 1991; Lahiri & Reetz, 2002, 2010) based on underspecification (Kiparsky, 1982 et seq.) predict asymmetrical judgments in lexical processing tasks; these have been supported in some psycholinguistic research showing that participants are more sensitive to noncoronal-to-coronal (**pop** → **top**) than to coronal-to-noncoronal (**top** → **pop**) changes or mispronunciations. Three experiments using on-line visual world procedures showed that 19-month-olds and adults displayed sensitivities to both noncoronal-to-coronal and coronal-to-noncoronal mispronunciations of familiar words. No hints of any asymmetries were observed for either age group. There thus appears to be considerable developmental continuity in the nature of early and mature lexical representations. Discrepancies between the current findings and those of previous studies appear to be due to methodological differences that cast doubt on the validity of claims of psycholinguistic support for underspecification.

Keywords

lexical representation; developmental continuity; mispronunciation processing; phonological details; underspecification

Adults exhibit impressive abilities in recognizing words in familiar languages. They can segment words instantaneously from continuous speech streams, abstract native phonemes effortlessly from speech signals characterized by lack of invariants, and distinguish known words from novel words with very high accuracy.

For learners to acquire adult-like language proficiency, experience with the phonology of the native language plays a central role. Studies have consistently shown that infants possess global perceptual sensitivities that can be adapted to learn the phonological categories of any language. For example, before six months, infants can distinguish phonetic categories that

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are not used in their native language, and it is not until the end of the first year of life that infants are fully tuned to language-specific speech structures (e.g., Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Werker, Gilbert, Humphrey, & Tees, 1981; Werker & Tees, 1984; Werker & Lalonde, 1988). Whether early lexical knowledge comprises native phonological details and whether the details are adult-like both in amount and in nature have been topics of debate.

Several early studies suggested that early lexical representations might be holistic and vague, with little or no detailed phonological information. For instance, children as old as eight years had been found to fail to discriminate native phonemes across a variety of tasks, including picture selection and phonological similarity judgment (Barton, 1976, 1980; Eilers & Oller, 1976; Garnica, 1973; Kay-Raining Bird & Chapman, 1998; Schvachkin, 1973). However, recent studies using less demanding experimental paradigms have shown that at least by the middle of the second year, lexical representations are detailed in terms of phonological features. Swingley & Aslin (2000) found that 14-month-olds are sensitive to 1-feature mispronunciations (“*vaby*”) of familiar words (“*baby*”). White & Morgan (2008) demonstrated that 19-month-old infants display graded sensitivity to varying degrees of onset mispronunciations of familiar words: as mispronunciations increasingly deviated from a correct form (/dog/) by one (/gog/), two (/k^og/), or three features (/sog/), infants’ proportional looking to a referent of the familiar target word decreased. The same pattern of response was replicated for coda mispronunciations (Ren & Morgan, 2011), vowel mispronunciations (Mani & Plunkett, 2011) and lexical tone mispronunciations (Ren & Morgan, 2013). Using a slightly different paradigm, Nazi (2005) showed that 20-month-olds can apply their detailed representation of native speech categories in learning minimal pairs of novel words (“*pize*” vs. “*tize*”). Adults have also been found to be affected by the degree of acoustic-phonetic mismatch during semantic priming (Connine, Titone, Deelman, & Blasko, 1997; Milberg, Blumstein, & Dworetzky, 1988) and visual word recognition (Tin, White, & Morgan, 2014). Thus, early and mature lexical representations both appear to be of commensurate with phonological detail.

However, although these previous studies have found striking developmental continuity in the *amount* of phonological details between early and mature lexical representations, whether the *nature* of the represented detail is stable across development is still not known. In particular, phonological theories of underspecification (Archangeli, 1988; Avery & Rice, 1989; Kiparsky, 1982) have suggested that certain unmarked feature values, such as coronal place of articulation, may be left unspecified or empty in underlying lexical representations (Kean, 1975). Such arguments are primarily motivated by differences in phonological processes between coronal and noncoronal segments. For example, in Catalan (Mascaro, 1976), backwards place of articulation assimilation occurs only for coronal stops, as in (1),

(1) Stop assimilation in Catalan:

<i>se[t]</i>	‘seven’
<i>se[m] mans</i>	‘seven hands’

<i>se[p] forcs</i>	'seven fires'
<i>se[b] beus</i>	'seven voices'
<i>se[d] dones</i>	'seven women'
<i>se[k] cases</i>	'seven houses'

whereas labial and velar stops do not undergo such assimilation.

(2) Stop assimilation in Catalan :

<i>ca[p]</i>	'no'
<i>ca[p] signe</i>	'no sign'
<i>po[k]</i>	'few'
<i>po[k] pa</i>	'few bread'
<i>po[k] sol</i>	'few sun'

Differences in phonological processes between coronal and noncoronal segments are also found in many other languages, such as English place assimilation (e.g. *sweet* [swi:t] *girl* is often pronounced as [swi:k] *girl*) (Gaskell & Marslen-Wilson, 1996) and so forth. Underspecification theory is thus in part an attempt to explain why pronunciations of nominally coronal segments in words are less faithful than are pronunciations of noncoronal segments.

Although underspecification was not advanced to explain speech perception, hypotheses predicting effects on spoken word recognition have been derived from this aspect of phonological theory (Lahiri & Marslen-Wilson, 1991; Lahiri & Reetz, 2002, 2010). For example, the Featurally Underspecified Lexicon (FUL) model (Lahiri & Reetz, 2002, 2010) predicts specific asymmetries in effects of mispronunciations. On this account, the place of articulation of the onset /d/ of the word *duck* is unspecified in lexical representation; consequently, mispronunciations in the onset of *duck* such as *guck* will not be incompatible with the underlying representation, and such mispronunciations should have minimal effects on lexical activation of *duck*. By contrast, the onset /g/ of the word *goose* is specified as [+velar] in the underlying lexical representation, so mispronunciations of the onset of *goose* such as *doose* will be incompatible with the underlying representation and thus will significantly disrupt lexical activation of *goose*.

Psycholinguistic studies using a variety of tasks have adduced evidence supporting predictions of the FUL model. For example, at temporally early stages of speech perception as found by ERP, German-speaking adults display asymmetric discrimination for mispronunciations of familiar words with coronal or noncoronal onsets (Friedrich, Lahiri, & Eulitz, 2008), word internal consonants (Friedrich, Eulitz, & Lahiri, 2006; Cornell, Lahiri & Eulitz, 2013), codas (Lahiri & van Coillie, 1999), and vowels (Lahiri & Reetz, 2010; Cornell, Lahiri, & Eulitz, 2011). Similar effects have also been found with English-speaking adults (Roberts, Wetterlin & Lahiri, 2013). Other studies have used gating and lexical decision procedures to demonstrate putative effects of underspecification in Bengali,

English, and German (Gaskell & Marslen-Wilson, 1996; Lahiri & Marslen-Wilson, 1991; Lahiri & Reetz, 2010; Wheeldon & Wasker, 2004).

A recent series of studies by Mitterer (2011), however, failed to find the asymmetries predicted by the FUL model. Mitterer conducted a series of visual-world studies in which Dutch-speaking adults saw four printed words arrayed on a screen and heard targets that varied from onset competitors by one (Experiments 1-3) or two (Experiment 4) features (see also McQueen & Viebahn, 2007). Adults looked more towards competitor words than phonologically unrelated distractor words, but there were no differences depending on phonological relations between target and competitor onsets.

In this article, we present a series of studies examining possible asymmetries in toddlers' processing of (mis)pronunciations of familiar words and compare toddlers' processing with adults' to examine the question of developmental continuity. That is, do toddlers' lexical representations have similar phonological details with adults' mature lexical representations in terms of featural (under)specification. The other goal of our studies was to ensure that the tasks used clearly tapped lexical representations. Unlike Mitterer (2011), we used a simplified visual-world procedure in which subjects saw pictured referents of familiar words. Associations between pronunciations and referents by definition involve the mental lexicon. By contrast, in languages with sub-logographic writing systems such as English, pronunciations can be readily generated for novel or nonce forms and thus relations between pronunciations and printed forms need not rely on lexical entries. Use of pictured referents also allowed us to use the same procedure, with only minor modifications, with both toddlers and adults. This will best enable us to address our fundamental goal: to determine whether the nature of phonological specification in the mental lexicon is stable across development.

Based on the underspecification account (Kiparsky, 1982 et seq.), the unmarked values are assumed to be the default values. Therefore, certain considerations, both theoretical and empirical, suggest that effects of underspecification might be observed most strongly in younger populations. For example, Optimality Theory (OT) analyses of child grammar (Gnanadesikan, 2004) have suggested that markedness constraints, which dis-prefer marked forms, outrank faithfulness constraints, which would have preserved those marked forms, in toddlers' early phonology.

Language experience may attenuate effects of underspecification. Certain accounts of early lexical representation have suggested that the degree of phonological specification correlates positively with the toddler's vocabulary size (Charles Luce & Luce, 1990, 1995; Storkel, 2002; Walley, 1993, 2005). According to the Lexical Restructuring Model (Metasala & Walley, 1998), for example, word learning can increase the specificity of infants' speech categorization and concomitantly increase in the specificity with which individual words are represented in the lexicon. As the child's vocabulary expands, the lexicon comes to contain more and more sets of similar sounding words. On such views, toddlers, whose vocabularies are markedly smaller, are more likely to have an underspecified lexicon than adults. Of course, adults know many more minimal pairs than do toddlers, many of which involve

coronal vs. noncoronal contrasts (e.g., *pop*, *top*, *cop*); suppression of underspecification might help to avoid false-alarm over-recognition of items with coronal segments¹.

To date, studies with infants and toddlers have found mixed evidence for early appearance of asymmetries predicted by underspecification. Dijkstra & Fikkert (2011), for example, habituated 6-month-old Dutch-learning infants to either repeated *taan* or *paan* tokens and then tested their ability to discriminate trials in which one or the other stimulus repeated versus trials in which the two stimuli alternated. Whereas infants habituated to *paan* discriminated the two types of trials, infants habituated to *taan* did not. Similarly, Tsuji, Mazuka, Cristia & Fikkert (2015) habituated 4-month-old Dutch-learning infants and 4-month-old Japanese-learning infants to either repeated *ompa* or *onta* tokens. Then, they tested the infants' ability to discriminate trials in which one or the other stimulus repeated versus trials in which the two stimuli alternated. For both language groups, whereas infants habituated to noncoronal stimuli (*paan*, *ompa*) discriminated the two types of trials, those habituated to coronal stimuli (*taan*, *onta*) did not. In both studies, the authors interpreted their findings in terms of underspecification: when the standard of comparison was coronal (*taan* or *onta*), the coronal feature for place of articulation was unspecified, and the noncoronal counterpart (*paan* or *ompa*) were compatible with the standard. However, when the standard of comparison was noncoronal (*paan* or *ompa*), the labial place of articulation was specified, the coronal counterpart (*taan* or *onta*) was not compatible with the standard, and *paan* vs. *taan* and *ompa* vs. *onta* were both discriminable.

Using a preferential looking mispronunciation task, van der Feest and Fikkert (2015) found that 20- and 24-month-old Dutch-learning toddlers showed significant differences in proportional looking times to referents of familiar words beginning with labials depending on whether they were correctly pronounced or mispronounced with coronal onsets. However, toddlers did not show differences in looking times when familiar words beginning with coronals were mispronounced with labial onsets. Similarly, Tsuji, Fikkert, Yamane & Mazuka (2016) tested one group of Dutch-learning and one group of Japanese-learning 18-month-olds on their sensitivities to coronal mispronunciations of novel words. They found lack of sensitivities to such mispronunciations for infants from both language groups. The procedures of these two studies both involved considerable stimulus repetition. That is, each toddler was exposed to a single target item, which was tested in *multiple* pronunciation conditions: In van der Feest & Fikkert, there are six items tested in correct pronunciations, and among the six items, four were tested with place of articulation mispronunciations, and four with voicing mispronunciations. Similarly, in Tsuji, Fikkert, Yamane & Mazuka, the two items were tested with correct pronunciations, mispronunciation changes to labial sounds, and mispronunciation changes to dorsal sounds.

¹Conversely, if perceptual effects of underspecification were not suppressed in adults, this might create pressure in the lexicon for avoiding such minimal pairs. A recent computational analysis of the CMU Pronouncing Dictionary by the second author of our paper (Cohen-Priva, 2012), however, suggests that this is not the case in English. There are 822 CVC minimal pairs in which coronal and non-coronal stop consonants contrast, and 748 such pairs in which two non-coronal stop consonants contrast. Overall, minimal pairs occur more often than would be expected by chance, given segment frequencies. For coronal/non-coronal minimal pairs, the observed/expected ratio is 2.05; for non-coronal/non-coronal pairs, the ratio is 2.09.

Less clear support for underspecification comes from a series of studies by Fennell and colleagues testing 14-month-old English-learning infants on their sensitivities to different directions of novel word mispronunciations using the “switch task” (Stager & Werker, 1997). Consistent with the underspecification hypothesis, an initial study (Fennell, 2007) showed that infants detected a labial-to-coronal switch but failed to detect a coronal-to-labial switch. However, inconsistent with the underspecification hypothesis, a follow-up study (Fennell, van der Feest, & Spring, 2010) showed that 14-month-olds were better able to detect a coronal-to-velar switch than a velar-to-coronal switch. To explain such findings, the author attributed the asymmetries to the fact that /b/</d/</g/ in acoustic variability in their experimental stimuli. Thus, the authors concluded that the asymmetries they observed might be better explained by acoustic properties of the segments than by their phonological status or (under)specification.

In this article, we examine possible asymmetries at the lexical level by comparing 19-month-old English-learning toddlers’ and English-speaking adults’ detection of correct and incorrect pronunciations of familiar words. We tested coronal-to-labial, labial-to-coronal, coronal-to-velar, and velar-to-coronal mispronunciations in an online word recognition task using a simplified version of the visual world paradigm. If toddlers’ lexical representations are unspecified for coronal place of articulation as predicted by the underspecification hypothesis, then we expect to see significant asymmetries: larger effects for labial-to-coronal and velar-to-coronal mispronunciations than for coronal-to-labial and coronal-to-velar mispronunciations. By using lexical specification as leverage, we hope to obtain a clearer picture of developmental (dis)continuity in the nature of lexical representations.

EXPERIMENT 1

White & Morgan (2008) introduced several refinements to the preferential looking mispronunciation task pioneered by Swingley & Aslin (2000). First, rather than displaying two referents with known labels in each trial, they paired a referent with a known label and a referent without a known label. The rationale for this modification was that known labels might reduce the sensitivity of the paradigm by repelling of mispronunciations towards the correct forms. For example, if a toddler were to see pictures of a baby and a car and hear a mispronunciation *vaby*, because that pronunciation is not a possible label for the car, changes in looking time relative to the correct pronunciation *baby* might be limited. They also tested each item on only a single trial. This modification is of importance for studies of asymmetries in speech perception, because testing items repeatedly raises possibilities of carry-over effects and may change the perceived nature of the task. In particular, whereas hearing *vaby* once may interrogate whether it is an acceptable pronunciation of *baby* (a perceptual task), hearing these two pronunciations multiple times might be construed as asking whether *vaby* is a plausible mispronunciation of *baby*. To find a solution to such a question, infants might need to draw on implicit metalinguistic knowledge. In this way, tasks with repetitions of stimuli may tap into different processing levels than on-line lexical processing.

Collectively, the modifications introduced by White & Morgan served to increase the power and sensitivity of the mispronunciation task: whereas earlier studies (Bailey & Plunkett,

2002; Swingley & Aslin, 2002) had failed to find graded effects depending on the numbers of features altered in mispronunciations, White & Morgan showed a strong linear effect of number of features altered in onset changes on toddlers' looking times. Here, we use White & Morgan's procedures to interrogate possible asymmetries in word recognition.

Experiments 1a and 1b were designed to establish whether 19-month-olds exhibit asymmetrical sensitivities to mispronunciations depending on whether the mispronunciations are from coronal to noncoronal segments or vice-versa. To address this question, we tested mispronunciations in consonantal onsets in Experiment 1a and codas in Experiment 1b, respectively.

Methods

Participants

Fifty-five 19-month-old English-learning infants were recruited from monolingual English-speaking families in Rhode Island and Massachusetts. Twenty-seven of these infants were tested on onset mispronunciations in Experiment 1a and twenty-eight were tested on coda mispronunciations in Experiment 1b. Nine participants were excluded from data analysis due to fussiness (4) or crying (3) or over 50% alternative language exposure (1). This left twenty-one 19-month-olds (mean age = 1;7;17) in Experiment 1a and twenty-six 19-month-olds (mean age = 1;7;23) in Experiment 1b, respectively.

Stimuli

Familiar labels comprised a set of words that are comprehended by the majority of infants by 14 months, according to the MacArthur CDI norms (Dale & Fenson, 1996). In each trial, infants saw two images, one depicting a referent of a familiar label, the other depicting a referent of an unfamiliar (to 19-month-olds) label. An example stimulus pair is depicted in Figure 1; a list of displayed objects is given in Appendix A for onset mispronunciations and in Appendix B for coda mispronunciations. Infants were tested in 18 trials. These included three trials with correctly pronounced coronal stops (e.g. *dog* or *cat*), three mispronounced coronal stops (e.g. *gog* or *cak*), three correctly pronounced noncoronal stops (e.g. *cat* or *dog*), three mispronounced noncoronal stops (e.g. *tat* or *dad*), three correctly pronounced familiar fillers (e.g. *hand*) and three novel fillers (e.g. *wrench*). Examples of (mis)pronunciations are given in Table 1 for onsets and Table 2 for codas. Familiarity of labels for target and distractor images was assessed via a parental questionnaire completed after the experiment session.

Mispronunciations involved only single-feature changes in place of articulation, and all mispronunciations resulted in non-words or in words judged unlikely to be familiar to infants at this age. Most of the words tested in the current study were monosyllabic, with only two exceptions (*baby* and *table*) for onsets in Experiment 1a due to the restricted vocabulary size of babies at 19 months. All stimuli were naturally produced by a trained female speaker of American English who produced the utterances with positive infant-directed affect. The mean length of target items across all conditions was 588.05 msec (SD = 78.58 msec); lengths of target items did not differ significantly across conditions, $F(3, 92) =$

0.036, $p = 0.991$. A complete list of words used in the current study and their accompanying images are provided in Appendix A for onsets and Appendix B for codas.

Pairings of familiar and unfamiliar objects remained constant across subjects. Assignment of stimulus pairs to pronunciation condition was counterbalanced across subjects (filler trials were constant across subjects). Half of the coronal items were mispronounced with a corresponding labial stop, and half were mispronounced with a velar stop. These were counterbalanced so that one sub-group heard two labial mispronunciations and one velar mispronunciation, while the other heard one labial mispronunciation and two velar mispronunciations. Similarly, the noncoronal items were evenly divided between labials and velars; one sub-group heard one correct labial pronunciation and two correct velar pronunciations, while the other heard two correct labial pronunciations and one correct velar pronunciation. Each item was presented to each infant one time only, i.e. either the correct form or the mispronounced form. Order of presentation was pseudo randomized online for each infant with the constraint that the first two trials always contained one correct filler trial and one novel filler trial.

Procedure

Testing was conducted in a sound-treated laboratory room. The parent sat with the child on his/her lap, while listening to instrumental music over noise-cancelation headphones to mask the audio stimuli. Approximately 90cm in front of the child were two 51cm flat-panel monitors mounted side-by-side, together subtending approximately 55 degrees of visual angle. A speaker was located centrally between the two monitors behind a pegboard panel. At the subjects' eye level, a blue light was mounted on the panel between the two monitors. The subjects were observed over a closed-circuit video system and recorded on a digital camcorder at 30 fps for later off-line coding. Speech stimuli were played at conversational level (70 dB).

An intermodal preferential looking procedure (IPLP) similar as that used in White & Morgan (2008) was used during the experiment. Each trial began with the blue light flashing until the subject fixated at midline. At that point, the experimenter turned off the center light and initiated the salience phase. During the salience phase, one object with a known label and a second object with unknown label were simultaneously displayed on the two monitors (see Figure 1). The two objects were displayed silently for 4 seconds to establish baseline looking preference. After the salience phase, the two monitors went dark, and infants' attention was then recaptured to midline to avoid contingencies between side of fixation at the end of the salience period and at the beginning of the test period.

After recentralization, the experimenter initiated the test phase. During the test phase, the audio stimulus (*Where's the X?*) was played, and immediately after that, the two visual stimuli were presented for 8 seconds. Following an interval of at least 1 second, the next trial commenced. Side of presentation of the familiar object was randomized between trials by the customized experimental software, but was consistent across salience and test phases within each single trial. The dependent measure was the change in proportional looking to the familiar object between the (silent) salience phase and the test phase. Of interest was whether looking behavior would differ as a function of the directions of mispronunciation.

Following the session, the parent completed the vocabulary questionnaire to verify on his/her toddler's comprehension and production of the stimulus items (familiar and unfamiliar).

Results and discussion

Results from the parental questionnaire indicated the items selected were appropriate for this sample of 19-month-olds. Of a scale of 3 (1 = only visually familiar; 2 = visually familiar and label known; 3 = visually familiar, label known and produced), labels for target images (used as familiar words) received an average score of 2.462 for Experiment 1a (SD = .242) and 2.462 for Experiment 1b (SD = .273), indicating that they were highly familiar to toddlers. Labels of distractor images² received an average score of 0.24 for Experiment 1a (SD = .235) and 0.301 for Experiment 1b (SD = .208), indicating that they were highly unfamiliar to toddlers. No labels of target images in Experiment 1a or 1b were scored 1. Labels of distractor images were scored 3 in 24 trials (of 360 total, 6.67%) in Experiment 1a, and in 32 trials (of 468 total, 6.84%) in Experiment 1b. These trials were all removed from further analyses.

Looking behavior was coded off-line frame-by-frame (1 frame = 33 msec) using in-house coding software. For the salience phase, looking behavior was coded for entire the 4s duration of the phase. For the test phase, looking behavior was coded only for the 3s following the onset of the first occurrence of the target word. This was done in order to include only subjects' initial response to the target word.

In the present case, two competing accounts make divergent predictions for the patterns of results that should be observed. On the underspecification (FUL) account, mispronunciations of segments that are underlyingly labial or velar should disrupt lexical recognition and access, whereas mispronunciations of underlyingly coronal segments should not; the data should follow the pattern shown in Figure 2. By contrast, on the account that segments are equivalently represented regardless of place of articulation, a main effect of (mis)pronunciation should obtain, but there should be no (mis)pronunciation-by-place of articulation interaction.

Overall summaries of the data for onsets in Experiment 1a and codas in Experiment 1b are shown in Figures 3 and 4, respectively. In both figures, proportional looking towards each of the objects in each trial was first computed over the total time the subject spent looking at both objects for that phase. Then, a difference score of proportional looking was computed using the following formula:

$$\%Looking(Familiar)_{Test} - \%Looking(Familiar)_{Salience}.$$

This formula measures the change in looking toward the familiar object after the target was named. Such difference scores allowed us to use each stimulus pair as its own baseline, controlling for differences in visual salience or inherent preference for a particular stimulus

²All these words were not used as experimental stimuli – just the images.

in each pairing. It is clear from inspection that the interactions predicted by the underspecification account did not materialize in our evidence.

The dependent measure of our statistical analyses was participants' success/failure to gaze at the target object at each time frame for each trial. In particular, if at a certain time frame of a trial the participant was looking at the target, we coded it as a 1 and otherwise we coded it as 0. The time course data can be found in Figure 5 for Experiment 1a and Figure 6 for Experiment 1b, respectively.

Given the binary data in each time frame for each trial, we conducted Bayesian Logistic Regressions with Mixed Effects Modeling. By specifying priors that are appropriate for each account, Bayesian data analyses (Kruschke, 2010; Gelman, Carlin, Stern & Rubin, 2004) can be computed that yield estimates of the posterior probabilities of the parameters, providing a principled quantitative evaluation of the credibility of the hypotheses under discussion. Fixed effects of the model included pronunciation and place of articulation as two discrete variables, time as a continuous variable, and their interactions. Random effects of the model include random intercepts and slopes for both subjects and items. Mathematical details of the model can be found in Supplementary Material II. The time window used for Experiment 1a was between 233.31 msec and 1899.81 msec after the initiation of each trial, and the time window used for Experiment 1b was between 233.31 msec and 1733.16 msec after the initiation of each trial. Following standard practice, data from the first 233.31 msec were excluded from analyses to allow for programming and execution of initial saccades. After 1899.81 msec (1733.16 msec for Experiment 1b), on average participants had reached the highest looking proportion to the target objects. This suggests that participants at this time point had achieved the highest degree of lexical activation for all the experimental conditions.

We first ran Bayesian Logistic Mixed Effects Regressions with non-informative priors. That is, conjugate priors were used for the parameters of the model with coefficients of (mis)pronunciation, place of articulation, time and the interaction between these factors were all set as normally distributed centered on zero. Standard deviations of normal distributions were set to follow a half gamma distribution with the rate parameter and the shape parameter both set as 0.01. This Bayesian method is similar to null hypothesis significance testing with Logistic Mixed Effects Modeling except that the mean and the variance of the regression coefficients were specified with conjugate prior distributions. In this way, we will be able to obtain the posterior distributions of these parameters which provides the information about the observed effect size. JAGS code for Logistic Mixed Effects Modeling with non-informative priors is given in Appendix E. For readers unfamiliar with Bayesian data analyses, results of NHST Logistic Mixed Effects Modeling are given in Supplementary Material II. Posterior distributions for two main effects and the interaction are shown in Table 3 for Experiments 1a and 1b.

For both experiments, zero was included in the 95% highest density intervals (HDIs) of the posterior distributions for the three-way interactions of (mis)pronunciation by place of articulation by time. These results suggest that during word activation, toddlers do not differentiate mispronunciation effects according to the place of articulations of the target

word for both onsets and codas. Moreover, the HDIs of the posterior distributions for the effect of (mis)pronunciation over time (i.e., time and pronunciation interaction) exclude zero for Experiment 1b, suggesting that 19-month-olds in this experiment were also sensitive to 1-feature mispronunciations of coda consonants in word recognition. By contrast, the effect of (mis)pronunciation over time (i.e., time and pronunciation interaction) does not exclude zero for Experiment 1a. Therefore, the lack of three-way interaction in this experiment participants could also suggest that 19-month-olds were not sensitive to 1-feature mispronunciations of onset consonants.

To examine this possibility and to further evaluate the underspecification and equivalent-representation accounts, we conducted Bayesian Model Comparisons. In particular, two sets of priors were established with equal probability, where one set supports the equivalent representation account and the other set supports the underspecification hypothesis. By specifying priors that are appropriate for each account, posterior probabilities were then computed for the observed data given each of the alternative accounts to provide a quantitative estimate of the relative credibility of the two accounts.

The two informed sets of priors were obtained through the following steps. First, we obtained data from Tin & Morgan (2014) who tested English-speaking adults on their sensitivities to 1-, 2- and 3-feature mispronunciations in word onset consonants. Using the correct mispronunciation and 1-feature mispronunciation data of this study, we created two separate datasets with one dataset supporting the underspecification hypothesis and the other dataset supporting the equivalent representation account. In the underspecification data, participants' response to (mis)pronunciations of coronal segments were made to be equal to their correct counterparts; and all of the effect of mispronunciation is assumed to reside in the noncoronal items. In the equivalent-representation data, participants' response to (mis)pronunciations of coronal segments were simply taken from their 1-feature mispronunciation counterpart in Tin & Morgan's data to model the fact that there was no (mis)pronunciation by place of articulation interaction. Then, the two datasets were tested with the same logistic mixed effects model as the one used for non-informative priors, and parameters of the model were estimated using Maximum Likelihood Estimation (MLE). Thus, two sets of coefficients were obtained and then entered into the Bayesian Model Comparison as two sets of prior distributions, with one set of coefficient representing the underspecification model and the other set representing the equivalent representation account. Specific values for the prior means of the coefficients under each model are given in Table 4. JAGS code for Bayesian Model Comparison can be found in Appendix F.

Given the onset data in Experiment 1a and 1b, the posterior probability of the model based on parameters derived from the underspecification account ($P(M_U|D)$) was both 0, whereas the posterior likelihood of the model based on parameters derived from the equivalent representation account ($P(M_{ER}|D)$) was 1 according to the MCMC estimation, which assumed the prior probability of the two sets of parameters to be equal. The ratio of these two likelihoods yields a Bayes factor of infinity. A Bayes factor of this magnitude is typically interpreted as "very strong" (Kass & Raftery, 1995) or "decisive" (Jeffries, 1961). Therefore, for the data in Experiment 1a and Experiment 1b, the equivalent representation parameters provide a credible account, whereas the underspecification parameters do not.

Therefore, in the range of reasonable priors, there are no values leading to anything other than supporting for an interpretation of equivalent specification.

Contrary to accounts for both infants (Dijkstra & Fikkert, 2011; Tsuji et al., 2015) and adults (Lahiri & Reetz, 2010), all our analyses indicate that 19-month-olds equivalently represent coronal and noncoronal consonants. This inconsistency with previous findings may in part be due to our use of on-line measurements of processing of correct and incorrect pronunciations in an intermodal preferential looking procedure. Previous studies of underspecification in adults have typically used other tasks, such as the oddball paradigm in EEG, gating or semantic priming, to examine effects of mispronunciations. It is thus unclear whether the reported results reflect procedural differences or developmental changes in lexical representation between infants' early lexical representation and adults' mature lexical representation. To disentangle this, in Experiments 2a and 2b, we employed a visual world paradigm mimicking the intermodal preferential looking procedure used for infants to test adults on their immediate responses to mispronunciations.

EXPERIMENT 2

The purpose of the two experiments was to test whether adults asymmetrically represent coronals and non-coronals using an on-line word recognition task. Experiments 2a and 2b addressed this question for consonantal onsets and codas, respectively.

As noted earlier, Mitterer (2011), using a procedure similar to ours, failed to find evidence for predicted asymmetries. Our studies differ from those of Mitterer's in several ways, most notably using images rather than printed words and examining effects of mispronunciations. We discuss ramifications of these differences later in Experiment 3.

Methods

Participants

Sixty-three mono-lingual English-speaking adults aged from 19 to 37 were recruited from students and staff members at Brown University. Thirty-one adults were tested in Experiment 2a for onsets, and thirty-two were tested in Experiment 2b for codas. Seven participants were excluded from data analysis due to failure in the eye tracker calibration (4), failure to follow instructions (2), and discomfort with the experimental settings (1). This left twenty-eight participants in each experiment.

Stimuli

Familiar stimuli comprised a set of highly frequent objects with familiar names; the distractors were comprised of a set of rare or fantastical objects, with their names unlikely to be known. An example stimulus pair is depicted in Figure 7.

One hundred and eight trials were used, with seventy-two experimental trials and thirty-six filler trials. Among the seventy-two experimental trials, there were eighteen correct coronal trials (e.g. duck/cat), eighteen mispronounced coronal trials (e.g. guck/cak), eighteen correct noncoronal trials (e.g. cat/duck), and eighteen mispronounced noncoronal trials (e.g. tat/du).

Among the thirty-two filler trials, there were eighteen correct fillers (e.g. *hand*) and eighteen novel fillers (e.g. *pruse*). According to the Corpus of Contemporary American English (Davies, 2011), mean log frequencies were 3.82 (SD = 0.61) for items with coronal onsets, 4.01 (SD = 0.57) for items with noncoronal onsets, 4.11 (SD = 0.56) for items with coronal codas, and 3.73 (SD = 0.70) for items with noncoronal codas. Differences in frequencies were not significant for onset items ($t(70) = -1.362, p = .177$), but items with coronal codas occurred more frequently than items with noncoronal codas ($t(70) = 2.591, p = .012$). Because our selection of items was constrained by image-ability and main effects of place of articulation were not of central interest, we judged these differences in item frequencies to be acceptable.

All stimuli were naturally produced by a trained female speaker of American English who produced the utterances with positive affect. The mean length of target items across all conditions was 564.05 msec (SD = 70.84 msec); lengths of target items did not differ significantly across conditions, $F(3, 140) = 1.036, p = 0.890$. The sets of non-filler items were counterbalanced across two subgroups: the items that one subgroup heard correctly pronounced, the other group heard mispronounced, and vice-versa. Complete lists of words used in the current studies are shown in Appendix C for onsets and Appendix D for codas; accompanying images are provided in Supplementary Material I.

As in Experiments 1, mispronunciations only involved changes in place of articulation. All mispronunciations resulted in non-words in English. Following the rationale described in Experiments 1, each item was presented to each participant one time only.

Procedure

The procedure was similar to that used in Experiments 1a and 1b. The experiment began with detailed written instructions on the computer screen, in which participants were told to click on the image to which the spoken word referred, using a provided mouse. Each trial began with a salience phase, in which participants saw pairs of images with no accompanying speech. Following re-centering of the participant's gaze on a fixation point, the pair of images reappeared, this time accompanied with a spoken label. In these experiments, the carrier phrase *Where's the* was eliminated from the test phase; participants heard only the isolated label³. Gaze was recorded by an ASL eye-tracker (all subjects in Experiment 2a, 20 subjects in Experiment 2b) or an SMI eye-tracker (eight subjects in Experiment 2b, after the ASL eye-tracker failed). For subjects tested on the ASL equipment, trials were terminated immediately after the mouse click. The SMI software did not allow trials to be terminated on mouse clicks; for subjects tested with this apparatus, trials continued for 4 seconds, at which point the fixation image for the next trial appeared on the screen. Regions of interest were defined based on the locations of the two images shown in each trial and were used to automatically code the eye-tracker output.

³The software we used for the toddler experiments allowed us to synchronize the appearance of the objects with the onset of the label; but we could not do that with the software used for the adult experiment. Therefore, to make sure that the subject heard the audio stimuli and saw the visual stimuli simultaneously, we removed the carrier phrase.

Results and discussion

Data are coded frame by frame using an in-house software for the eye-tracking data, with each frame 16.67 milliseconds. Overall summaries of the data of the proportional looking to target are shown in Figures 8 and 9 for onsets in Experiment 2a and codas in Experiment 2b, respectively. It is clear from inspection that the underspecification account was again not well supported in our evidence.

As in Experiment 1, we conducted Bayesian statistical analyses using the same mixed effects logistic regression. Time course data are depicted in Figure 10 and Figure 11 for Experiment 2a and 2b, respectively.

As in Experiment 1, we first conducted the Bayesian Mixed Effects Logistic Regressions using non-informative priors; and time windows were selected for analyses to capture lexical activation in all experimental conditions. In particular, 216.71 to 1016.87 and 216.71 to 1667 msec after the initiation of each trial were selected for analyses in Experiment 2a and 2b, respectively.

Posterior distributions for comparisons testing the two main effects and the interaction are summarized for Experiment 2a and 2b in Table 5.

For both experiments, the 95% HDIs of the posterior distributions for (mis)pronunciation by time interaction exclude zero, suggesting that participants in both experiments were sensitive to 1-feature mispronunciations over time. By contrast, zero was not excluded from the HDIs of the posterior distributions for the (mis)pronunciation by place of articulation interaction for either experiment: these effects are not credibly different from zero.

We next ran Bayesian Model Comparisons to assess the underspecification and equivalent-representation accounts using the two informed sets of priors as in Experiment 1. Given the coda data in Experiment 2b, the posterior likelihood of the model based on parameters derived from the underspecification account ($P(M_U|D)$) was 0, whereas the posterior likelihood of the model based on parameters derived from the equivalent representation account ($P(M_{ER}|D)$) was 1. The ratio of the two likelihoods yields a decisive Bayes factor of infinity. Therefore, for the data in both Experiments 2a and 2b, the equivalent representation parameters provide absolutely credible accounts for the data, whereas the underspecification parameters do not. We also conducted time course analyses for data in both experiments. Such results are consistent with previous analyses: no evidence for predicted psycholinguistic effects of underspecification were found. Details can be found in Supplementary Material II.

Like 19-month-olds, when assessed in a task that measured on-line processing, adult participants were sensitive to one-feature mispronunciations. Taking together findings in Experiment 1 and Experiment 2, we conclude that toddlers' early lexicon is adult-like in terms of phonological details, suggesting substantial developmental continuity between early and mature lexical representations.

Also like 19-month-olds, adults were not sensitive to the direction in which those mispronunciations took place. These findings suggest that for purposes of immediate processing, coronal and noncoronal onsets and codas are equally represented with phonological details at the lexical level for adults, contrary to predictions from the underspecification hypothesis.

EXPERIMENT 3

Does the visual world procedure used in Experiments 1 and 2 tap into underlying lexical representations? In our procedure, subjects saw images of possible referents in the salience phase before they heard any label in the test phase; both toddlers (Mani & Plunkett, 2010) and adults (Meyer, Belke, Telling, & Humphreys, 2007) can generate implicit labels upon seeing referents with known names. The task in Experiments 1 and 2 could thus be conceived as recruiting “a phono-lexical matching process between the heard label and the [implicit] label for the perceived object [that determines] the goodness-of-fit” (Mayor & Plunkett, 2014, p. 93). This suggests an alternative explanation for our failure to find asymmetries: if the implicit labels are full-fledged surface forms with values filled in for any features that are unspecified in underlying representations, our task amounts to asking subjects to compare one surface form to another, and no asymmetries would be predicted on any account.

This concern applies even more strongly to Mitterer’s (2011) studies, which used printed words as referents rather than images. Although printed referents circumvent limitations of imageability and allow a wider choice of stimulus words (McQueen & Viebahn, 2007), use of such referents introduces additional interpretive difficulties. First, orthographic similarities may influence competitor activations (Salverda & Tanenhaus, 2010). In Mitterer’s experiments, competitors differed from targets in the initial letter (and onset phone), but then shared several subsequent letters. Thus competition may have occurred at an orthographic level in addition to or even in place of phonological competition.

Salverda and Tanenhaus argue that “in the absence of sufficient preview time to read the printed words, orthographic rather than phonological similarity will mediate the mapping between an unfolding spoken word and potential printed referents” (p. 1109). To counteract unwanted orthographic effects, Mitterer allowed subjects additional time to read the printed words before hearing the spoken stimuli (personal communication, 7/26/2014). However, while increased preview time may have possibly eliminated orthographic effects, subjects were more likely to have generated representations of productive pronunciations either through explicit subvocal rehearsal (Baddeley & Hitch, 1975) or via implicit access to articulatory codes for the printed stimuli (Wheat, Cornelissen, Frost, & Hansen, 2010; Klein et al., 2014). Again, if such productive phonological representations are fully specified surface forms, there will be no cause for asymmetric effects on any account.

To resolve this problem, we conducted a new version of the adult onset study. The stimuli and design were the same as in Experiment 2a, except that the salience phase was eliminated so that the pictures appeared synchronously with the onset of the label at the start of each trial. In this fashion, subjects were not afforded opportunities to generate implicit

pronunciations but rather could only compare the heard label with existing lexical representations to determine goodness-of-fit.

Methods

Participants

Twenty-four mono-lingual English-speaking adults aged from 19 to 57 were recruited from students and staff members at Brown University.

Stimuli

The same stimuli were used as in Experiment 2a.

Procedure

The salience phase used in earlier experiments was eliminated; only the test phase as described earlier was used. Participants' eye-movements were recorded by an SMI eye-tracker. Each trial began with a fixation point in the center of the screen. Once the participant fixated the fixation point for 500 msec, the trial began automatically: the label was played and the two pictures appeared simultaneously.

Results and Discussion

As in Experiment 2a, data was coded frame by frame using an in-house software with each time window 16.67 milliseconds; and the dependent measure was participants' success/failure of looking at the target object at each time frame. The time window used for data analyses was between 216.71 msec and 1066.88 msec after the onset of each trial, when word activation was still taking place for all the four different conditions. To provide a first inspection of the data, looking proportions to target in each condition are shown in Figure 12 and time course data are shown in Figure 13. It is clear from inspection that the underspecification account was again not well supported in our evidence.

As in Experiment 2, we conducted series of Bayesian analyses to evaluate which model (underspecification (FUL) vs. equivalent specification) best captures the parameter distributions of the data. We first conducted an analysis using non-informative priors. Results for the posterior distributions of each estimated coefficients can be found in Table 6.

We then specified priors that were appropriate for the underspecification and equivalent representation accounts to provide principled quantitative estimates of the relative credibility of the two accounts.

The posterior likelihood of the model based on parameters derived from the underspecification account ($P(M_U|D)$) was 0.00009, whereas the posterior likelihood of the model based on parameters derived from the equivalent representation account ($P(M_{ER}|D)$) was 0.99991 according to the MCMC estimation. As in Experiment 2, we assumed the prior probability of the two sets of parameters to be equal. The ratio of these two likelihoods yields a decisive Bayes factor of infinity.

In this experiment, the salience phase was dropped from the procedure, so that the patterns of data cannot be ascribed to artifactual comparisons of surface forms but rather reflect the architecture of feature specification in the lexicon. Like Experiments 2a and 2b, Experiment 3 indicates that coronal and noncoronal features are equally specified in the adult lexicon and that psycholinguistic claims based on underspecification (i.e. FUL model) do not hold true.

GENERAL DISCUSSION

Given the central role of word learning in language acquisition, a critical question regarding developmental continuity is whether toddlers' early lexical representations resemble adults' mature lexical representations. Studies in recent years have shown that early and mature lexical representations do include similar quantities of phonological detail (Swingley & Aslin, 2000; White & Morgan, 2008). However, it has not previously been investigated whether the quality of phonological details in toddlers' representations is also adult-like.

As the first attempt in investigating whether certain phonological features are consistently (under)specified across development we have reported a series of studies, two with toddlers and three with adults, using a simplified visual-world procedure that directly and immediately taps into lexical activations. The results of our studies are uniform: for both toddlers and adults, for both onsets and codas, with and without prior exposure to images, looking to the referents of familiar words was decreased when those words were mispronounced.

These results replicated findings in the literature that toddlers are sensitive to one-feature mispronunciations (Swingley & Aslin, 2000; White & Morgan, 2008), indicating that early lexical representations include very detailed information in terms of phonological features. Given that we also found the same results with adult listeners, we can conclude that toddlers' early lexical representations are adult-like in terms of the amount of phonological details. Therefore, contrary to claims of phonological reorganization (Storkel, 2002; Walley, 2005) our findings suggest developmental continuity between toddlers' early lexicon and adults' mature lexicon.

More importantly, in no case, did the nature of the mispronunciations make any difference: whether coronals were mispronounced as noncoronals or noncoronals were mispronounced as coronals, looking time to the familiar referent decreased in much the same proportion. Such findings suggest that both coronal feature and noncoronals are equally specified in both 19-month-olds' and adults' lexical representations. Our results are clearly inconsistent with predictions from underspecification-based accounts such as the Featurally Underspecified Lexicon model (Lahiri & Reetz, 2002, 2010). Our adult studies mirror those of Mitterer (2011), who tested Dutch-speaking adults. As we did, Mitterer consistently failed to find evidence for asymmetries predicted by the FUL model: looking to printed-word onset competitors differing from targets by one or two features was the same regardless of featural relations. Thus, across procedures, languages, and ages, converging results indicate that there are no differences in lexical representations of coronal versus noncoronal segments.

Nevertheless, as noted earlier, a number of studies have found evidence for the asymmetries predicted by accounts such as the FUL model. For example, in a gating task, Bengali speakers gave few CVN responses to early gates of CVN stimuli, consistent with the claim that oral vowels in Bengali are unspecified for nasality (Lahiri & Marslen-Wilson, 1991). Lahiri & van Coillie (1999) found that the German word for “railway”, *bahn* could still prime the word for “train” when it was mispronounced as *bahm*. However, the word for “tree”, *baum*, did NOT prime the word for “bush” when it was mispronounced as *baun*. In several follow-up studies, Lahiri and colleagues replicated the same pattern of asymmetry for word onsets (Fredrich, Eulitz & Lahiri, 2008), medial positions (Friedrich, Eulitz & Lahiri, 2006), and vowels (Obleser, Lahiri & Eulitz, 2004; Lahiri & Reetz, 2010) using priming or lexical decision tasks. In addition, using the oddball paradigm, Cornell, Lahiri & Eulitz (2011, 2013) and Eulitz & Lahiri (2004) found similar patterns of asymmetry at an early stage of speech perception (around 250 milliseconds) for English consonant onsets and vowels and German vowels respectively.

Van der Feest and Fikkert (2015) used an Intermodal Preferential Looking Procedure similar to ours and showed that 20- and 24-month-old Dutch-learning toddlers respond asymmetrically to place-of-articulation mispronunciations of coronal- and labial-initial familiar words. Using a novel word-learning task, Tsuji et. al. (2016) also found a lack of sensitivities to mispronunciation changes to coronal words with 18-month-old Japanese and Dutch toddlers. Thus, across procedures, languages, and ages, converging results indicate that there *are* differences in representations of coronal versus noncoronal segments.

How can these contradictory findings be reconciled? One possible approach lies in considering the nature of the representations engaged in the various procedures. The visual world/mispronunciation task that we used here exploits relations between word-forms and referents – relations that are fundamentally lexical. We will argue below that some of the tasks that have yielded evidence apparently in support of lexical underspecification engage only phonetic representations, whereas other recruit, in addition, strategic, metalinguistic representations.

As also suggested by Mitterer, findings from studies that measure early stages of processing may reflect phonetic processing. Recent EEG studies examining underspecification have mostly used the oddball paradigm, in which participants passively listen to stimuli changing from standard to nonstandard forms (Cornell, Lahiri & Eulitz, 2011 & 2013; Eulitz & Lahiri, 2004). In all these studies, asymmetrical sensitivities are often found at temporally very early stages. Moreover, no lexical activation is required for this sort of task: stimuli may comprise nonce items as well as existing words.

Nor is it clear whether results from studies with young infants supporting underspecification-based accounts can reasonably be construed as reflecting properties of lexical representations. Tsuji et. al. (2015) tested 4-month-old Dutch-learning infants and Japanese-learning infants in a habituation paradigm on their sensitivities to different directions of changes between nonce items *ompa* and *onta* and found discrimination of the items when infants were habituated to *ompa* but not to *onta*. Similarly, Dijkstra & Fikkert (2011) tested six-month-old Dutch infants in a habituation paradigm on their sensitivities to

different directions of changes between nonce items *paan* and *taan* and found discrimination of the items when infants were habituated to *paan* but not to *taan*. By six months, infants can form representations that have at least some lexical properties: they can use their own names and other highly familiar forms as anchors for segmentation (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005), and they can associate some form of reference with well-known words (Bergelson & Swingley, 2012). Moreover, by eight months, infants can use syllable combinations extracted from statistical learning tasks in word-like fashions (Erickson, Thiessen, & Graf Estes, 2014; Saffran, 2001). However, there is no evidence that infants can do any of these things with the repeated, isolated forms characteristic of habituation stimuli, or that they assign them any sort of lexical representation. The conservative interpretation, thus, is that infants treat such stimuli as mere phonetic sequences.

If subjects are processing stimuli solely at a phonetic level in these procedures, it is possible that the asymmetries found in these studies may reflect statistical or distributional differences between speech categories in competition. Coronal sounds are more frequent and more variable as a class than are noncoronal sounds; we argue that either of these properties is sufficient for producing asymmetrical judgments.

Phoneticians and phonologists have often noted that, cross-linguistically, coronal sounds are more frequent in occurrence than noncoronal sounds (e.g., Maddieson, 1984; Keating, 1990). To supplement these observations, we tabulated the frequency of occurrence of relevant classes of sounds in the CALLHOME database for several languages in diverse language families, including Arabic (Kilany, Gadalla, Yacoub, & McLemore, 2002), Japanese (Kobayashi, Crist, Kaneko, & McLemore, 1996), and Spanish (Garrett, Morton, & McLemore, 1996). Results from our tabulations are shown in Table 7. In each of these languages, coronal segments as a class are at least twice as frequent as either labial or velar segments. The same pattern generally holds with respect to stop consonants as a class and with respect to minimally contrastive pairs of segments.

Japanese is exceptional: velar stops (in particular, /k/ and /kʲ/) occur more often than coronal stops (in particular, /t/). Thus, Japanese may provide an interesting test-bed for teasing apart effects of processing at featural and segmental levels⁴. As discussed previously, Tsuji et al. (2015) showed that Japanese-learning 4-month-olds display asymmetric perceptions of coronal and labial segments, discriminating changes from a labial to a coronal but not vice versa. This finding is consistent with the frequency-based account proposed here (see Table 7): changes from less frequent categories to more frequent categories are easier to detect than the other way around. The critical question here is whether this effect is reversed when coronal and *velar* segments are considered in similar speech perception tasks that do not involve lexical activation.

If we conceive of speech sound categories as attractors (see also Tuller et. al., 1994) with strength proportional to the experienced frequency of constituent features or sounds, then categories with higher frequencies of occurrence may tend to pull in, or assimilate,

⁴This also depends on whether /ts/ and /tʃ/ are perceived as allophones of /t/. If not, there are less /t/ than /k/. Otherwise, there are less /k/ than /t/ and Japanese would be similar to many other languages.

exemplars of less frequent speech categories, especially when the two categories are close with each other in perceptual space (Anderson, Morgan, & White, 2003). Since coronal sounds/place of articulation occur more often, noncoronal sounds are more likely to be perceived as coronal sounds than vice versa. Feldman, Griffith & Morgan (2009) elaborated this idea on a more quantitative basis. Conceiving of speech perception as a process that uses Bayesian inference to reconstruct the stimulus from noise, their computational model suggested that, given a set of speech categories c and observed data d , then according to Bayes' rule, the posterior probability of any given speech category is given by $P(c|d) = P(d|c)P(c) / \sum_c P(d|c)P(c)$. Differences in the frequencies of phonetic categories correspond to differences in their prior probabilities $P(c_i)$. This difference, as modeled by a bias term of magnitude, $\log \frac{P(c_2)}{P(c_1)}$, can cause a shift in the discriminative boundary between the two categories under comparison (c_1 and c_2), the higher the prior of a specific category, the more likely that a given stimulus will be classified in this category. Therefore, in cases such as discrimination of repetitions of *taan* from alternations of *taan* and *paan*, multiple categories come into play, and the log ratio influences the outcomes of competitions. Here, if the attractor for /t/ (or *taan*) is sufficiently more powerful than the attractor for /p/ (or *paan*), repetitions of *taan* and alternations of *taan* and *paan* may not be discriminable. On this view, the 6-month-olds tested by Dijkstra & Fikkert (like the 4-month-olds tested by Tsuji et al.) came to their study with somewhat more experience with coronals than with labials, though with relatively little experience overall. Habituation with *taan* served to strengthen further the relatively strong /t/ (*taan*) attractor, so that after habituation, infants' ability to discriminate repetitions of *taan* from alternations of *taan* and *paan* was diminished. Other infants were habituated with *paan*; for these infants, habituation served to strengthen the relatively weak /p/ (*paan*) attractor, leveling the competitive field so that after habituation, infants' ability to discriminate repetitions of *paan* from alternations of *taan* and *paan* was left intact (or perhaps enhanced). In the case of adult subjects in oddball tasks, well-established coronal attractors are stronger than noncoronal attractors so that changes from coronal standards to noncoronal (mis)pronunciations will be more difficult to detect.

Coronal sounds may also have greater variability than their noncoronal counterparts, not so much due to their greater susceptibility to effects of coarticulation as to the facts that coronals appear in wider ranges of contexts and are more likely to be subject to phonological alternations than are noncoronals. When coarticulatory contexts are controlled, coronals may display less variability in place of articulation than do labials or velars (Sussman, McCaffrey, & Matthews, 1991; Sussman, Hoemeke, & McCaffrey, 1992). However, coronals typically appear in a much wider range of coarticulatory context than do noncoronals. In English, for example, of 45 possible onset clusters, only four (e.g., *quick*) do not include a coronal segment, while of 73 possible monomorphemic coda clusters, only three (e.g. *stink*) do not include a coronal segment. As we noted earlier, in Catalan, coronal nasals can assimilate in place to following stops, while velar or palatal nasals remain unchanged (Mascaro, 1976). Similarly, in English, coronal word-final obstruents may assimilate in place to following consonants, whereas noncoronal obstruents do not (Marslen-Wilson, Nix, & Gaskell, 1995). Thus, whereas *sweet* may appear in assimilated forms (*sweep boy*, *sweek girl*), *deep* and *steak* cannot (**deet tank*, **steat dinner*).

As a first approximation, segment variability can be estimated by computing the likelihood that a given underlying segment will surface as a different segment. Cohen Priva (2012) used a modified Levenshtein distance metric to align underlying (dictionary) forms and phonetic realizations in the Buckeye Natural Speech Corpus (Pitt, Johnson, Raymond, Hume & Fosler-Lussier, 2007) and to create an articulatory confusion matrix for English segments. Of the 43,915 underlying coronal stop tokens, 21,576 (49%) were pronounced as some other segment, whereas of the 64,288 underlying noncoronal stop tokens, only 2,997 (5%) were pronounced as an alternative segment, a significant difference, $t(4) = 248.83$, $p < .001$.⁵ Moreover, coronal stops have larger numbers of alternative manifestations (24 for /d/ and 19 for /t/) than do noncoronal stops (/b/, /g/, /p/, and /k/ each have 7 deviant forms). A chi-square goodness-of-fit test comparing against a theoretical expectation of 12.67 for the three voiced cells and 11 for the three unvoiced cells, i.e., testing against the hypothesis that number of variants does not vary across different places of articulation, yields a $\chi^2(2)$ of 23.94, $p < .001$.

Ren & Austerweil (2017) modeled effects of variability in the following way: If we conceive of speech sound categories as attractors with strength proportional to the experienced frequency of constituent sounds, then categories with broader variability are amenable to a wider range of sounds. Such categories may assimilate exemplars from less variable categories, especially when the two categories are in perceptual proximity. Because coronal sounds have greater variability than noncoronal sounds, they are more likely to assimilate noncoronal sounds than vice versa. Thus, coronals mispronounced as noncoronals are more acceptable in perception than vice versa. Their Bayesian model confirmed this hypothesis: categories with higher variability have higher posterior probabilities than categories with lower variability (Figure 14).

Perceptual asymmetries resembling those purportedly due to underspecification have been observed in other cognitive domains as well, where they have often been ascribed to effects of differences in variability. Quinn, Eimas & Rosencrantz (1993), for example, found that 4-month-olds habituated to pictures of cat faces could easily detect a change to a picture of a dog face, but infants habituated to dog faces failed to detect a change to a cat face. A series of follow-up studies investigating this asymmetry confirmed that the dog stimuli were more variable in appearance and that when variability was equated across categories the asymmetry disappeared (Eimas, Quinn & Cowan, 1994; Mareschal, French & Quinn, 2000; Mareschal, & Quinn, 2001). Similarly, in music perception, Delbé, Bigand & French (2006) examined effects of variability by training non-musician adults with two distributions of pitch sequences differing in variability and then testing them on sensitivities to the two directions of changes. Their results indicated that changes from the less variable category to the more variable category are more detectable than vice versa. Therefore, while underspecification may cause asymmetry, asymmetry is not necessarily a consequence of underspecification.

⁵Cohen Priva also found that coronals (9% of all segments; 20% of stops) were more likely to be deleted than noncoronals (5% of all segments, 4% of stops).

To recap, some of the tasks that have been used in studies supporting underspecification-based accounts such as the Featurally Underspecified Lexicon model engage only phonetic representations. During this stage of word recognition, speech perception is affected by the statistical properties of native speech categories, such as frequency of occurrence and variability of the speech category. We have argued that perceptual asymmetries can occur at this level, and may be the consequence of differences in statistical properties – frequency and/or variance – of the categories under comparison. Thus, rather than claiming that perceptual asymmetries originates from the lexical level where different phonological features are specified in different manners, we argue that asymmetries found in studies reviewed above are phonetic in nature. Moreover, rather than arguing that perceptual asymmetries are consequences of universal grammar, we argue that they may arise due to domain-general computational properties of cognition and depend on experience with input. Regardless of whether our account is correct, however, evidence from procedures such as the oddball task cannot bear on lexical underspecification, because such tasks do not necessarily engage lexical representations.

We note that some recent theoretical developments reject distinctions between pre-lexical and lexical representations (e.g., Arnold et al, 2017; Baayen, Shaoul, Willits, & Ramscar, 2015). On this view, asymmetric results such as those just described may arise from on-going adjustments of perception that are sensitive to both present and past statistical properties of experience (e.g., Marsolek, 2008), where the statistical properties that are relevant may depend on the nature of the task.

Other tasks that have been used to support underspecification-based accounts, such as lexical decision and semantic priming, however, clearly do engage lexical representations. Here the critical difference between studies that have found evidence consistent with predictions from underspecification and those that have not appears to involve the number of times items were presented for judgments. In both our studies and those of Mitterer (2011), items were presented for judgment one time only; the asymmetries characteristic of underspecification were not observed. Item repetition is central to some of the tasks that have supported psycholinguistic claims of underspecification. In ERP studies, some of which have also incorporated behavioral lexical decision tasks, items are repeated multiple times so that responses may be averaged, filtering noise. In gating studies, auditory stimuli are presented repeatedly, with progressively less truncation, while subjects are asked to guess which word they have heard. Lahiri & Marslen-Wilson (1991) report data on 11 gates per item. Priming and lexical decision procedures do not require item repetition, but in studies using these techniques that have supported underspecification, item repetition has been the rule. For example, in Roberts, Wetterlin & Lahiri (2013) in which a delayed semantic priming task was used, each testing item was repeated 4 times. In Friedrich, Lahiri and Eulitz (2008), Experiment 2, which used auditory priming, each testing item was also repeated 4 times. Similarly, in a study with toddlers somewhat similar to our own, both van der Feest and Fikkert (2015) and Tsuji et. al. (2016)⁶ presented target items multiple times each. Most tellingly, lexical decision tasks have consistently failed to find evidence for

⁶An alternative explanation for Tsuji et. al. is that the less detectability they found for coronal mispronunciations reflects a domain general perceptual bias. Participants were trained on coronal words only in this design. As suggested in a vast majority of studies in

underspecification when there was no item repetition (e.g. Friedrich, Lahiri, & Eulitz, 2006; Experiment 1 in Friedrich, Lahiri, & Eulitz, 2008).⁷

A voluminous literature has considered effects of item repetitions in memory and lexical decision tasks (e.g., Britt, Mirman, Kornilov, & Magnuson, 2014; Dutilh, Krypotos, & Wagenmakers, 2011; Forbach, Stanners, & Hochhaus, 1974; Rugg, 1990); a comprehensive review of this literature is beyond the scope of this article. However, item repetitions affect behavior in a variety of ways: latencies become shorter, speed of information processing increases, and responses biases may be adjusted. Judging the same items repeatedly also gives subjects additional opportunities to invoke strategies and may fundamentally change the perceived nature of the task. For example, whereas hearing *guck* once may interrogate the degree to which it activates *duck* - a perceptual task - hearing these two pronunciations multiple times might be construed as asking whether *guck* is a plausible mispronunciation of *duck*. This latter is a metalinguistic task; subjects may use their (implicit) knowledge that coronals frequently assimilate in place to preceding or following segments whereas noncoronal segments do so rarely if at all to judge that *guck* may be a plausible mispronunciation of *duck*, but *tat* is not a plausible mispronunciation of *cat*. Tasks in which responses are influenced by supra-lexical, metalinguistic knowledge cannot provide decisive evidence on lexical underspecification: underspecification predicts asymmetries in judgments, but asymmetries in judgments are not all attributable to underspecification.

To summarize our claims, we believe that there is developmental continuity for both the phonetic and phonological/lexical stages of processing. For phonetic processing, we propose that it is continuously asymmetrical over development. This is because in non-referential tasks that only involves speech processing without lexical activation, such as Dijkstra & Fikkert (2011) for 6-month-old infants and the EEG studies by Lahiri and colleagues, findings almost always suggested that the processing is asymmetrical due to the emergence of unequal category variance and frequency of occurrence at this processing stage.

For lexical processing, we propose that it is continuously symmetrical over development. This is because in referential tasks and in designs where the same items do have repetitions in different experiment condition, we almost always found symmetrical processing, as shown in the five experiments we reported in the manuscript as well as in Mitterer (2011). Therefore, in infants' early lexical representations and adults' mature lexical representations the coronal feature and the noncoronal feature are equally detailed specified.

cognitive psychology, such a paradigm per se renders the training item more typical than the non-training items. Thus the training item is often referred to as the cognitive reference point after Rosch (1975). Changes from typical items to atypical are more difficult to detect than vice versa. Such asymmetries have been found for not only word stimuli, but also a great variety of other cognitive domains such as color (Polk, 2002) and faces (Goldstone & Steyvers, 2001) etc.

⁷One possible exception might be Lahiri & Reetz (2010), which used a delayed priming task in which items were presented one time only. The authors report that mispronunciations of unspecified [+ coronal] vowels did not inhibit priming (priming = 15.37ms, $t = 1.99$; $p = .047$) whereas mispronunciations of specified vowels did inhibit priming (priming = 9.27ms, $t = 1.05$; $p > .05$). However, the authors failed to test the difference between these conditions directly, and it is doubtful whether the 6 millisecond difference was credibly non-zero.

CONCLUSION

Recent research has indicated that toddlers' and adults' lexical representations contain comparable amounts of phonological detail; the purpose of the current research was to examine the *nature* of phonological detail in toddlers' and adults' lexical representations, asking whether toddlers and adults are equally sensitive to mispronunciations of familiar words involving different directions of place of articulation changes. Previous research, using a variety of methods, had found evidence suggesting that both younger infants and adults are more sensitive to noncoronal-to-coronal than to coronal-to-noncoronal changes. However, our studies with 19-month-olds, using a simplified visual world task that immediately and directly assessed lexical activation did not provide evidence for any such asymmetry. A trio of follow-up studies with adults, using the same sort of task, also failed to reveal any asymmetries. These findings resolved our initial question: details in toddlers' and adults' lexical representations are similar both in extent and nature; specifically, coronal and noncoronal stops are represented with equal detail both in toddlerhood and adulthood.

These findings, however, raised another question: why have some procedures, but not others, yielded the sorts of perceptual asymmetries predicted by underspecification-based psycholinguistic accounts? A careful review of the literature shows that some of the tasks that have yielded evidence claimed to be consistent with underspecification engage only phonetic representations. We argued that such results are better explained by appealing to statistical properties of phonetic categories in competition; regardless, such results are not germane to claims of lexical underspecification. Other tasks that have yielded evidence consistent with underspecification and that clearly do engage lexical representations are characterized by repeated trials demanding judgments of the same items. Among other things, this allows for the intrusion of metalinguistic knowledge, rendering such tasks indecisive with respect to lexical underspecification. Thus, whereas underspecification as a phonological hypothesis may be useful for purposes of linguistic description, the status of psycholinguistic accounts based on underspecification is, at best, uncertain.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Appendix A.: Assignment of stimulus pairs to conditions in Experiment 1a















1. Experimental Design





Images		Label		
Familiar	Unfamiliar	Group1	Group2	Condition
dog	stag	gog	dog	coronal
door	drill	boor	door	coronal
duck	mole	buck	duck	coronal
table	vase	table	pable	coronal
toy	tent	toy	koy	coronal
TV	cage	teevee	keevee	coronal
baby	tapir	baby	daby	noncoronal
book	horn	book	dook	noncoronal
car	pump	tar	car	noncoronal
cat	squid	tat	cat	noncoronal
girl	sloth	girl	dirl	noncoronal
pig	mantis	tig	pig	noncoronal
ball	hive	hive	hive	novel filler
bottle	wrench	wrench	wrench	novel filler
foot	hut	hut	hut	novel filler
bath	reel	bath	bath	correct filler
bed	punch	bed	bed	correct filler
shoe	pulley	shoe	shoe	correct filler

2. Pictures used for visual display

Target Name	Familiar	Unfamiliar
dog		
door		

Target Name	Familiar	Unfamiliar
duck		
table		
toy		
TV		
baby		
book		
car		

Target Name	Familiar	Unfamiliar
cat		
girl		
pig		
ball		
bottle		
foot		
bath		













Target Name	Familiar	Unfamiliar
bed		
shoe		


Appendix B.: Assignment of stimulus pairs to conditions in Experiment 1b

1. Experimental Design

Images		Label		
Familiar	Unfamiliar	Group1	Group2	Condition
hat	vase	hat	hap	coronal
cat	stag	cat	cak	coronal
foot	gem	foot	fook	coronal
hand	drill	hang	hand	coronal
bed	hut	beb	bed	coronal
bird	mantis	birb	bird	coronal
cup	crown	cut	cup	noncoronal
sock	punch	sot	sock	noncoronal
duck	mole	dut	duck	noncoronal
dog	tapir	dog	dod	noncoronal
crib	cage	crib	crib	noncoronal
bib	strut	bib	bid	noncoronal
bath	pulley	bath	bath	correct filler
book	reel	book	book	correct filler
door	hive	door	door	correct filler
cheese	wrench	wrench	wrench	novel filler
car	pump	pump	pump	novel filler
ball	horn	horn	horn	novel filler

2. Pictures used for display

Target Name	Familiar	Unfamiliar
hat		
cat		
foot		
hand		
bed		
bird		

Target Name	Familiar	Unfamiliar
cup		
sock		
duck		
dog		
crib		
bib		
bath		

Target Name	Familiar	Unfamiliar
book		
door		
cheese		
car		
ball		

Appendix C.: Assignment of stimulus pairs to conditions in Experiment 2a

Experimental Design (see supplementary materials for pictures used for display)

Images		Label		Conditions
Familiar	Unfamiliar	Group1	Group2	
dove	1	dove	bove	coronal
donkey	2	donkey	bonkey	coronal
diver	3	diver	biver	coronal

	Images		Label		Conditions
	Familiar	Unfamiliar	Group1	Group2	
dome	4	dome	bome	coronal	
diamond	5	diamond	biamond	coronal	
dolphin	6	dolphin	bophin	coronal	
dipper	7	bipper	dipper	coronal	
doctor	8	boctor	doctor	coronal	
dish	9	bish	dish	coronal	
dice	10	bice	dice	coronal	
diary	11	biary	diary	coronal	
desert	12	besert	desert	coronal	
desk	13	desk	gesk	coronal	
disk	14	disk	gisk	coronal	
duck	15	duck	guck	coronal	
diaper	16	giaper	diaper	coronal	
daisy	17	gaisy	daisy	coronal	
donut	18	gonut	donut	coronal	
toe	19	toe	koe	coronal	
TV	20	TV	KV	coronal	
tent	21	tent	kent	coronal	
tank	22	tank	kank	coronal	
ticket	23	ticket	kicket	coronal	
tissue	24	tissue	kissue	coronal	
tower	25	kower	tower	coronal	
tail	26	kail	tail	coronal	
taxi	27	kaxi	taxi	coronal	
toilet	28	koilet	toilet	coronal	
tadpole	29	kadpole	tadpole	coronal	
tie	30	kie	tie	coronal	
turkey	31	turkey	purkey	coronal	
tape	32	tape	pape	coronal	
turtle	33	turtle	purtle	coronal	
table	34	table	pable	coronal	
tiger	35	tiger	piger	coronal	
toad	36	toad	poad	coronal	
bench	37	dench	bench	noncoronal	
boat	38	doat	boat	noncoronal	
bone	39	doan	boat	noncoronal	
bowl	40	dowl	bowl	noncoronal	
boy	41	doy	boy	noncoronal	
book	42	dook	book	noncoronal	
box	43	box	dox	noncoronal	

Images		Label		
Familiar	Unfamiliar	Group1	Group2	Conditions
bath	44	bath	dath	noncoronal
bird	45	bird	dird	noncoronal
bat	46	bat	dat	noncoronal
boot	47	boot	doot	noncoronal
bus	48	bus	dus	noncoronal
coach	49	toach	coach	noncoronal
cotton	50	totton	cotton	noncoronal
couch	51	tauch	couch	noncoronal
cage	52	tage	cage	noncoronal
cougar	53	tougar	cougar	noncoronal
keg	54	teg	keg	noncoronal
cushion	55	cushion	tushion	noncoronal
curtain	56	curtain	turtain	noncoronal
kettle	57	kettle	tettle	noncoronal
camel	58	camel	tamel	noncoronal
canoe	59	canoe	tano	noncoronal
candy	60	candy	tandy	noncoronal
pear	61	tare	pear	noncoronal
pasta	62	tasta	pasta	noncoronal
pizza	63	tizza	pizza	noncoronal
piano	64	piano	tiano	noncoronal
pencil	65	pencil	tencil	noncoronal
parrot	66	parrot	tarrot	noncoronal
girl	67	girl	dirl	noncoronal
gift	68	gift	dift	noncoronal
goose	69	goose	doose	noncoronal
garlic	70	darlic	garlic	noncoronal
ghost	71	dhost	ghost	noncoronal
garden	72	darden	garden	noncoronal
ear	73	ear	ear	correct filler
fan	74	fan	fan	correct filler
spoon	75	spoon	spoon	correct filler
tree	76	tree	tree	correct filler
hand	77	hand	hand	correct filler
hat	78	hat	hat	correct filler
bread	79	bread	bread	correct filler
flag	80	flag	flag	correct filler
foot	81	foot	foot	correct filler
ladder	82	ladder	ladder	correct filler
fox	83	fox	fox	correct filler

Images		Label		
Familiar	Unfamiliar	Group1	Group2	Conditions
guitar	84	guitar	guitar	correct filler
comb	85	comb	comb	correct filler
mango	86	mango	mango	correct filler
pen	87	pen	pen	correct filler
vase	88	vase	vase	correct filler
wine	89	wine	wine	correct filler
watch	90	watch	watch	correct filler
bermate	91	bermate	bermate	novel filler
dalok	92	dalok	dalok	novel filler
dwatch	93	dwatch	dwatch	novel filler
golpsle	94	golpsle	golpsle	novel filler
gomtox	95	gomtox	gomtox	novel filler
boupet	96	boupet	boupet	novel filler
lepter	97	lepter	lepter	novel filler
nando	98	nando	nando	novel filler
nescot	99	nescot	nescot	novel filler
quish	100	quish	quish	novel filler
fansel	101	fansel	fansel	novel filler
fapton	102	fapton	fapton	novel filler
holek	103	holek	holek	novel filler
stipe	104	stipe	stipe	novel filler
swike	105	swike	swike	novel filler
topal	106	topal	topal	novel filler
twipter	107	twipter	twipter	novel filler
suple	108	suple	suple	novel filler

**
The numbers in the column are numbered novel objects. Since there is no name for these objects, we used numbers to label them. See Figure 6 for an example of one of these novel objects, and see supplementary materials for a complete list of the novel objects used in the current experiment.

Appendix D.: Assignment of stimulus pairs to conditions in Experiment 2b

Experimental Design (see supplementary materials for pictures used for display)

Display		Label		
Familiar	Unfamiliar	Group1	Group2	Conditions
bed	1	bed	beb	coronal
bread	2	bread	breab	coronal
beard	3	beard	bearb	coronal

	Display		Label		Conditions
	Familiar	Unfamiliar	Group1	Group2	
bird	4	birb	bird	coronal	
food	5	foob	food	coronal	
mold	6	molb	mold	coronal	
head	7	head	heab	coronal	
spade	8	spade	spabe	coronal	
cloud	9	cloud	cloub	coronal	
bud	10	bub	bud	coronal	
blade	11	blabe	blade	coronal	
mud	12	mub	mud	coronal	
gold	13	gold	golg	coronal	
blood	14	blood	bloog	coronal	
slide	15	slide	slige	coronal	
thread	16	threag	thread	coronal	
sword	17	sworg	sword	coronal	
crowd	18	crowg	crowd	coronal	
cat	19	cat	cak	coronal	
boot	20	boot	buk	coronal	
foot	21	foot	fook	coronal	
boat	22	boak	boat	coronal	
goat	23	goak	goat	coronal	
suit	24	suik	suit	coronal	
jet	25	jet	jek	coronal	
fruit	26	fruit	fruik	coronal	
root	27	root	ruk	coronal	
scout	28	scouk	scout	coronal	
knight	29	knightk	knight	coronal	
nut	30	nuk	nut	coronal	
net	31	net	nep	coronal	
flute	32	flute	flupe	coronal	
light	33	light	lipe	coronal	
gut	34	gup	gut	coronal	
sprout	35	sproup	sprout	coronal	
skate	36	skape	skate	coronal	
crib	37	crib	crib	noncoronal	
crab	38	crab	crad	noncoronal	
shrub	39	shrub	shrud	noncoronal	
orb	40	ord	orb	noncoronal	
probe	41	prode	probe	noncoronal	
club	42	clud	club	noncoronal	
tube	43	tube	tude	noncoronal	

	Display		Label		Conditions
	Familiar	Unfamiliar	Group1	Group2	
tub	44	tub	tud	noncoronal	
swab	45	swab	swad	noncoronal	
flag	46	flad	flag	noncoronal	
pig	47	pid	pig	noncoronal	
plug	48	plud	plug	noncoronal	
frog	49	frog	frod	noncoronal	
dog	50	dog	dod	noncoronal	
keg	51	keg	ked	noncoronal	
fig	52	fid	fig	noncoronal	
crag	53	crad	crag	noncoronal	
drug	54	drud	drug	noncoronal	
book	55	boot	boot	noncoronal	
snake	56	snake	snate	noncoronal	
truck	57	truck	trut	noncoronal	
clerk	58	clert	clerk	noncoronal	
stick	59	stit	stick	noncoronal	
elk	60	elt	elk	noncoronal	
stork	61	stork	stort	noncoronal	
crook	62	crook	crot	noncoronal	
yolk	63	yolk	yolt	noncoronal	
soap	64	soat	soap	noncoronal	
scope	65	scote	scope	noncoronal	
tape	66	tate	tape	noncoronal	
scalp	67	scalp	scalt	noncoronal	
drop	68	drop	drot	noncoronal	
jeep	69	jeep	jeet	noncoronal	
strap	70	strat	strap	noncoronal	
chop	71	chot	chop	noncoronal	
pope	72	pote	pope	noncoronal	
gun	73	gun	gun	correct filler	
hand	74	hand	hand	correct filler	
apple	75	apple	apple	correct filler	
ear	76	ear	ear	correct filler	
cheese	77	cheese	cheese	correct filler	
cream	78	cream	cream	correct filler	
door	79	door	door	correct filler	
pen	80	pen	pen	correct filler	
nose	81	nose	nose	correct filler	
mouse	82	mouse	mouse	correct filler	
wolf	83	wolf	wolf	correct filler	

Display		Label		
Familiar	Unfamiliar	Group1	Group2	Conditions
hat	84	hat	hat	correct filler
peach	85	peach	peach	correct filler
clock	86	clock	clock	correct filler
grape	87	grape	grape	correct filler
mouth	88	mouth	mouth	correct filler
fish	89	fish	fish	correct filler
brush	90	brush	brush	correct filler
shrok	91	shrok	shrok	novel filler
klup	92	klup	klup	novel filler
ralk	93	ralk	ralk	novel filler
blerm	94	blerm	blerm	novel filler
dalp	95	dalp	dalp	novel filler
dwatch	96	dwatch	dwatch	novel filler
slem	97	slem	slem	novel filler
prack	98	prack	prack	novel filler
pruse	99	pruse	pruse	novel filler
troge	100	troge	troge	novel filler
gompt	101	gompt	gompt	novel filler
plaft	102	plaft	plaft	novel filler
slopt	103	slopt	slopt	novel filler
laust	104	laust	laust	novel filler
drept	105	drept	drept	novel filler
monge	106	monge	monge	novel filler
nelp	107	nelp	nelp	novel filler
thraft	108	thraft	thraft	novel filler

** The numbers in the column are numbered novel objects. Since there is no name for these objects, we used numbers to label them. See Figure 6 for an example of one of these novel objects, and see supplementary materials for a complete list of the novel objects used in the current experiment.

Appendix E.: JAGS Code for Bayesian Logistic Mixed Effects Modeling with NonInformative Priors

```

$$PREFORMATTXTIN$$modelstring = "model { for (index in 1:length(y) )
{ y[index] ~ dbern( mu[index]) mu[index] <- 1/(1+exp(-$$/PREFORMATTXTIN$$
$$PREFORMATTXTIN$$ (b0[SubjID[index], ItemID[index]]*Intercept[index]
+b1[SubjID[index], ItemID[index]]*T1[index]+b2[Sub
bjID[index], ItemID[index]]*Pronunciation[index]$$/PREFORMATTXTIN$$
$$PREFORMATTXTIN$$+b3[SubjID[index], ItemID[index]]*POA[index]
+b4[SubjID[index], ItemID[index]]*Pronunciation.T1[inde x]
+b5[SubjID[index], ItemID[index]]*POA.T1[index]$$/PREFORMATTXTIN$$

```

```

$$PREFORMATTEXTIN$$+b6[SubjID[index],ItemID[index]]*Pronunciation.POA[index]
+b7[SubjID[index],ItemID[index]]*Pronunciation.POA.T1[index])) }$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# An item cannot be both coronal and noncoronal so random
effects of items are only valid in some $$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# coefficients$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$for( i in 1 : nSubj ){ for(k in 1:nItem) {$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0[i,k]<-b0.fix +b0.subj[i]+b0.item[k] b1[i,k]<-b1.fix
+b1.subj[i] b2[i,k]<-b2.fix +b2.subj[i]+b2.item[k] b3[i,k]<-b3.fix
+b3.subj[i]+b3.item[k] b4[i,k]<-b4.fix +b4.subj[i] b5[i,k]<-b5.fix
+b5.subj[i] b6[i,k]<-b6.fix +b6.subj[i]+b6.item[k] b7[i,k]<-b7.fix
+b7.subj[i]$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$} }$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.fix~dnorm(0, pow( abs( tau.fix[1] ) + .001 , -2 ))
b1.fix~dnorm(0, pow( abs( tau.fix[1] ) + .001 , -2 )) b2.fix~dnorm(0,
pow( abs( tau.fix[1] ) + .001 , -2 )) b3.fix~dnorm(0, pow( abs( tau.fix[1] )
+ .001 , -2 )) b4.fix~dnorm(0, pow( abs( tau.fix[1] ) + .001 , -2 ))
b5.fix~dnorm(0, pow( abs( tau.fix[1] ) + .001 , -2 )) b6.fix~dnorm(0,
pow( abs( tau.fix[1] ) + .001 , -2 )) b7.fix~dnorm(0, pow( abs( tau.fix[1] )
+ .001 , -2 ))$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$for ( j in 1:8)$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$${$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$tau.fix[j]~dgamma(1,1) $$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$for ( i in 1:nSubj) {$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.subj[i]~dnorm(0, pow(abs( sigma0 ) + .001 , -10 ))$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$} tau.subj[1]~dgamma(1,1) $$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$for ( k in 1:nItem) {$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.item[k] ~dnorm(0, pow(abs(sigma1 ) + .001 , -10)) #
assuming homogeneity of variance for b0.item for each item$$/PREFORMATTEXTIN$
$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$sigma0 ~ dgamma(1, 1) sigma1 ~ dgamma(1, 1) $$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$

```

Appendix F.: JAGS code for Bayesian Model Comparison

```

$$PREFORMATTEXTIN$$modelstring = "model { for (index in 1:length(y) )
{ y[index] ~ dbern( mu[index]) mu[index] <- 1/(1+exp(-$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0[SubjID[index],ItemID[index]]*Intercept[index]
+b1[SubjID[index],ItemID[index]]*T1[index]+b2[Su

```

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bjID[index],ItemID[index]]*Pronunciation[index]$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$+b3[SubjID[index],ItemID[index]]*POA[index]
+b4[SubjID[index],ItemID[index]]*Pronunciation.T1[inde x]
+b5[SubjID[index],ItemID[index]]*POA.T1[index]$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$+b6[SubjID[index],ItemID[index]]*Pronunciation.POA[index]
+b7[SubjID[index],ItemID[index]]*Pronunciation.POA.T1[index]))$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# priors for the coefficients for( i in 1 : nSubj )
{ for(k in 1:nItem) {$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0[i,k]<-b0.fix +b0.subj[i]+b0.item[k] b1[i,k]<-b1.fix
+b1.subj[i] b2[i,k]<-b2.fix +b2.subj[i]+b1.item[k] b3[i,k]<-b3.fix
+b3.subj[i]+b2.item[k] b4[i,k]<-b4.fix +b4.subj[i] b5[i,k]<-b5.fix
+b5.subj[i] b6[i,k]<-b6.fix +b6.subj[i]+b3.item[k] b7[i,k]<-b7.fix
+b7.subj[i]$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$#--hyperpriors for the fixed effects--#$$/PREFORMATTEXTIN$
$
$$PREFORMATTEXTIN$$# mean$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.fix~dnorm(mu0[modelIndex], pow( abs( tau.fix[1] )
+ .001 , -10 )) mu0[1]<--3.440e-01 # MLE estimation b0~N(-0.26797,0.15406)
mu0[2]<--5.306e-01$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b1.fix~dnorm(mu1[modelIndex], pow( abs( tau.fix[2] )
+ .001 , -10 )) #delta[modelIndex])# mu1[2]<-7.344e-01 # MLE estimation
b1~N(-0.28267,0.01924) mu1[1]<-1.396e+00$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b2.fix~dnorm(mu2[modelIndex], pow( abs( tau.fix[3] )
+ .001 , -10 )) # delta2[modelIndex])# mu2[1]<-8.746e-01 # MLE estimation
b2~N(0.35110,0.02789) mu2[2]<-3.036e-13$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b3.fix~dnorm(mu3[modelIndex], pow( abs( tau.fix[4] )
+ .001 , -10 )) # delta3[modelIndex]) # mu3[1]<--1.447e-14 # MLE estimation
b3~N(0.03680,0.02733) mu3[2]<--8.746e-01$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b4.fix~dnorm(mu4[modelIndex], pow( abs( tau.fix[5] )
+ .001 , -10 )) # adelta4[modelIndex]) # mu4[1]<-6.620e-01 # MLE estimation
b3~N(-0.20495,0.03920) mu4[2]<-1.055e-14$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b5.fix~dnorm(mu5[modelIndex], pow( abs( tau.fix[6] )
+ .001 , -10 )) mu5[1]<--8.674e-15 mu5[2]<--6.620e-01$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b6.fix~dnorm(mu6[modelIndex], pow( abs( tau.fix[7] )
+ .001 , -10 )) mu6[1]<-1.750e-14 mu6[2]<-8.746e-01$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b7.fix~dnorm(mu7[modelIndex], pow( abs( tau.fix[8] )
+ .001 , -10 )) mu7[1]<-1.016e-14 mu7[2]<-6.620e-01$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# variance for( j in 1:8)$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$${$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$tau.fix[j]~dgamma(0.02,0.02) $$/PREFORMATTEXTIN$$

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$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# hyperpriors for the random effects$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# for subjects # mean$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$for( i in 1 : nSubj )$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$${$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.subj[i]~dnorm(0, pow( abs( tau.subj[1] ) + .001 ,
-10 )) # here we assume homogeneity of variance for all the random effects$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b1.subj[i]~dnorm(0, pow( abs( tau.subj[2] ) + .001 ,
-10 )) b2.subj[i]~dnorm(0, pow( abs( tau.subj[3] ) + .001 , -10 ))
b3.subj[i]~dnorm(0, pow( abs( tau.subj[4] ) + .001 , -10 ))
b4.subj[i]~dnorm(0, pow( abs( tau.subj[5] ) + .001 , -10 ))
b5.subj[i]~dnorm(0, pow( abs( tau.subj[6] ) + .001 , -10 ))
b6.subj[i]~dnorm(0, pow( abs( tau.subj[7] ) + .001 , -10 ))
b7.subj[i]~dnorm(0, pow( abs( tau.subj[8] ) + .001 , -10 )) $$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# varianceZ for (j in 1:8)$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$${$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$tau.subj[j]~dgamma(0.01,0.01) }$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# for items # mean for(k in 1:nItem) {$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b0.item[k]~dnorm(0, pow( abs( tau.item[1] ) + .001 ,
-10 )) # here we assume homogeneity of variance for all the random effects
for items$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$b1.item[k]~dnorm(0, pow( abs( tau.item[2] ) + .001 ,
-10 )) b2.item[k]~dnorm(0, pow( abs( tau.item[3] ) + .001 , -10 ))
b3.item[k]~dnorm(0, pow( abs( tau.item[4] ) + .001 , -10 )) }$$/
PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# variance for (h in 1:4)$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$${$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$tau.item[h]~dgamma(0.01,0.01) }$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$# hyperpriors for modelin modelIndex ~ dcat(modelProb[])
modelProb[1] <- .50 modelProb[2] <- .50$$/PREFORMATTEXTIN$$
$$PREFORMATTEXTIN$$}$$/PREFORMATTEXTIN$$

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HIGHLIGHTS

- This paper addresses the question of developmental continuity in infant and adult lexical representations using (under)specification of phonetic features as leverage.
- Our findings suggest that infants and adults represent phonetic features similarly in lexical representations, supporting the hypothesis of developmental continuity.
- In addition, our findings replicated a majority of previous studies and suggested that by the middle of the second year of life, toddlers are sensitive to one-feature mispronunciations of familiar words, suggesting that the amount of feature representation in early lexicon includes very detailed information.
- Most importantly, across five visual world experiments, we consistently found evidence against the psycholinguistic prediction of underspecification. In particular, mispronunciations in coronal and noncoronal place of articulation equally severely impair lexical activation, indicating that coronal features are not underspecified either in toddlers' early lexicon or in adults' mature lexicon.
- We suggest that previous psycholinguistic findings for perceptual asymmetries that support the notion of underspecification may have either tapped onto the pre-lexical processing or reflected meta-linguistic knowledge of different speech categories.

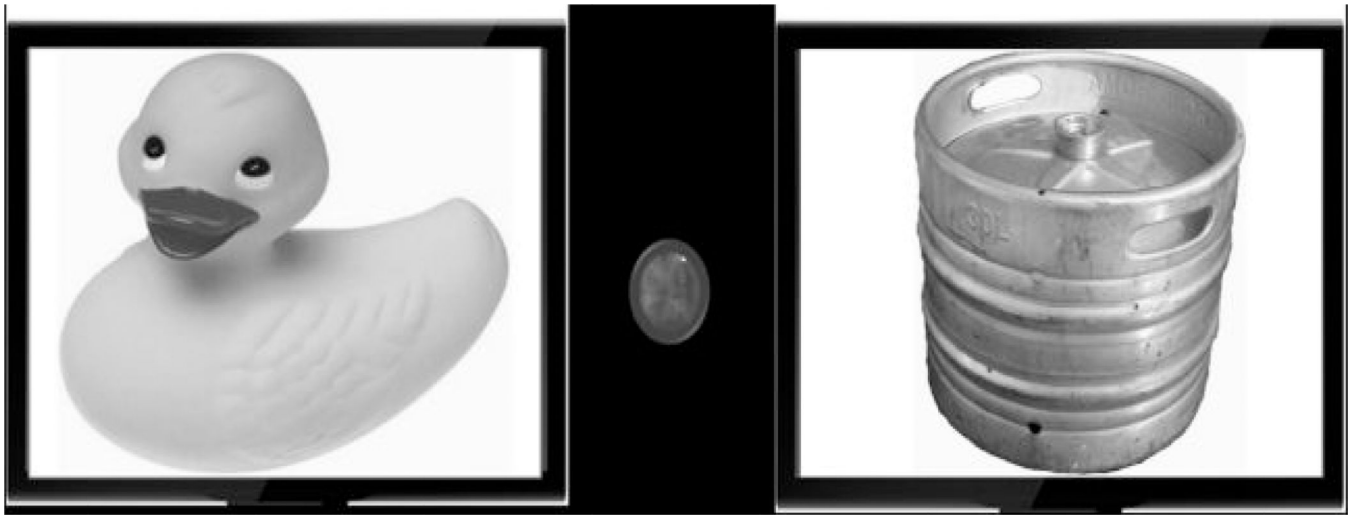


Figure 1.
Sample visual stimulus pair in Experiments 1a & 1b.

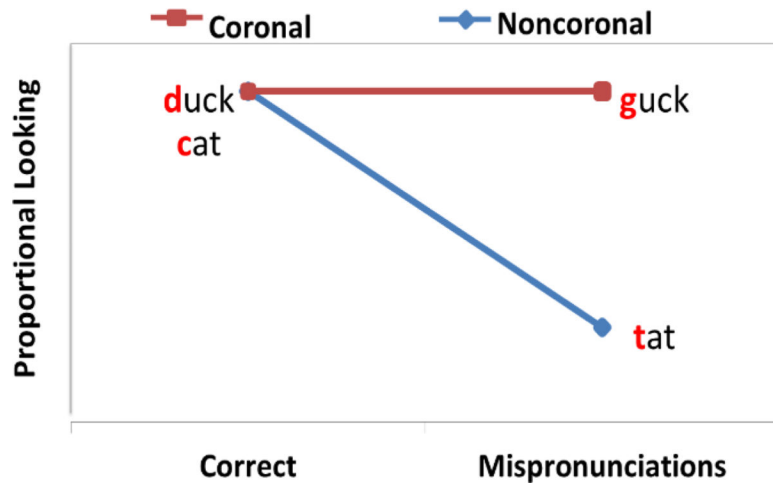


Figure 2.
Predicted results from the hypothesis of underspecification.

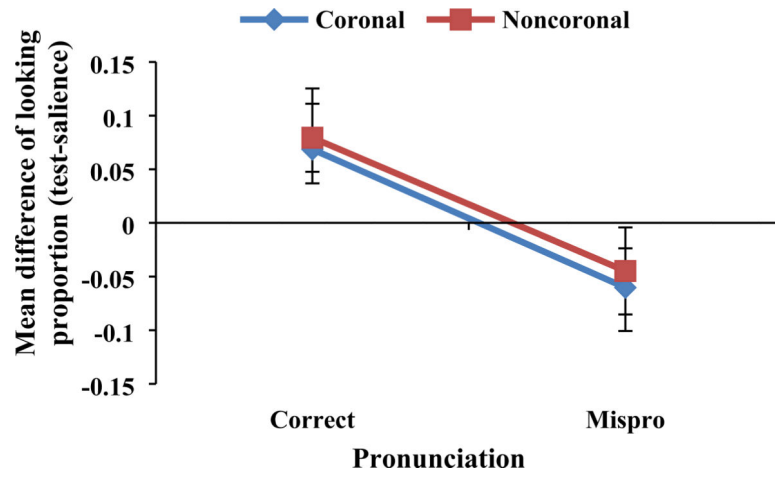


Figure 3.
Experiment 1a: Toddlers' sensitivities to different directions of onset mispronunciations.
Error bars show two standard errors computed via subject-wise non-parametric

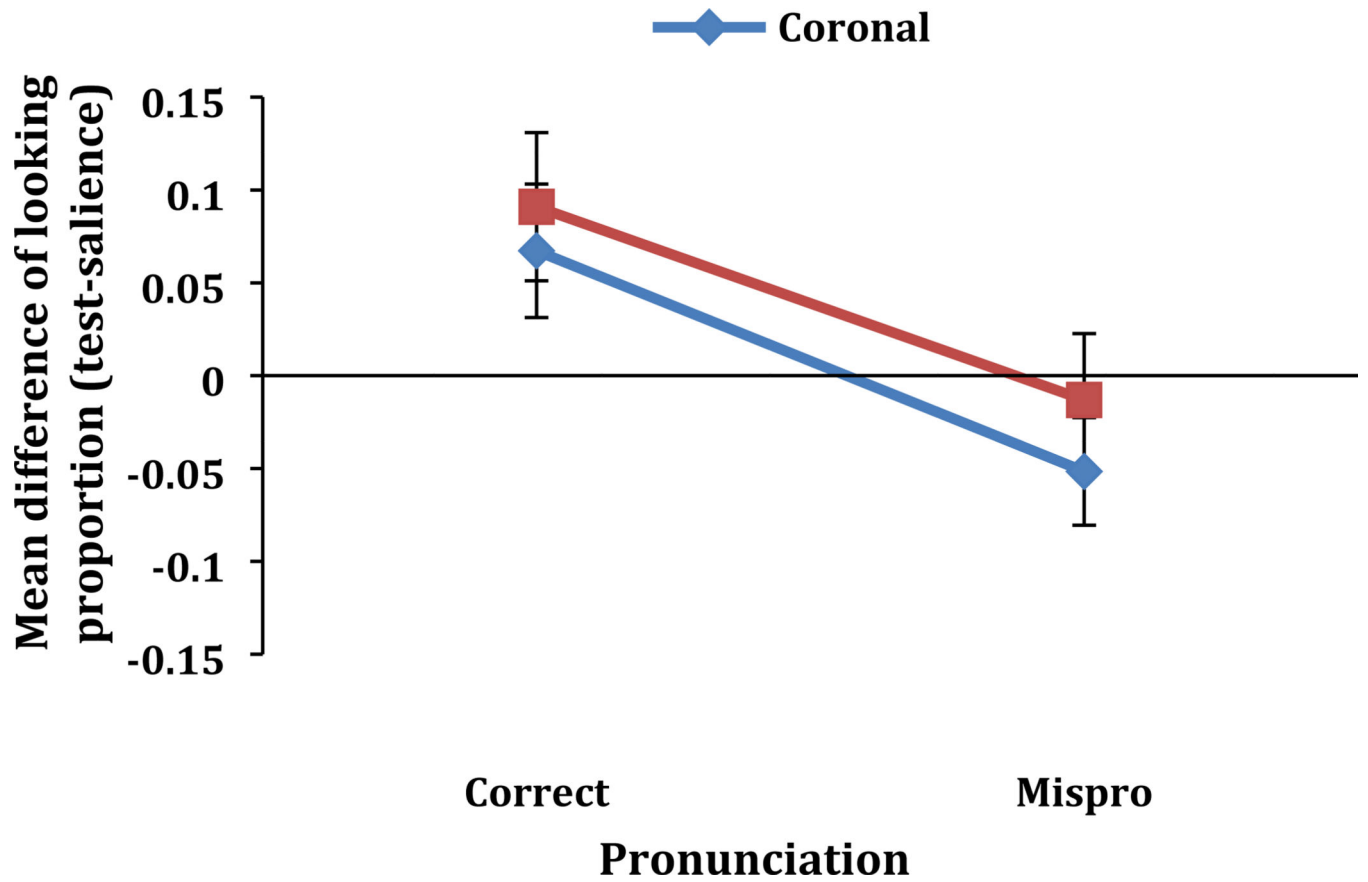


Figure 4. Experiment 1b: Toddlers' sensitivities to different directions of coda mispronunciations. Error bars show two standard errors computed via subject-wise non-parametric bootstrap.

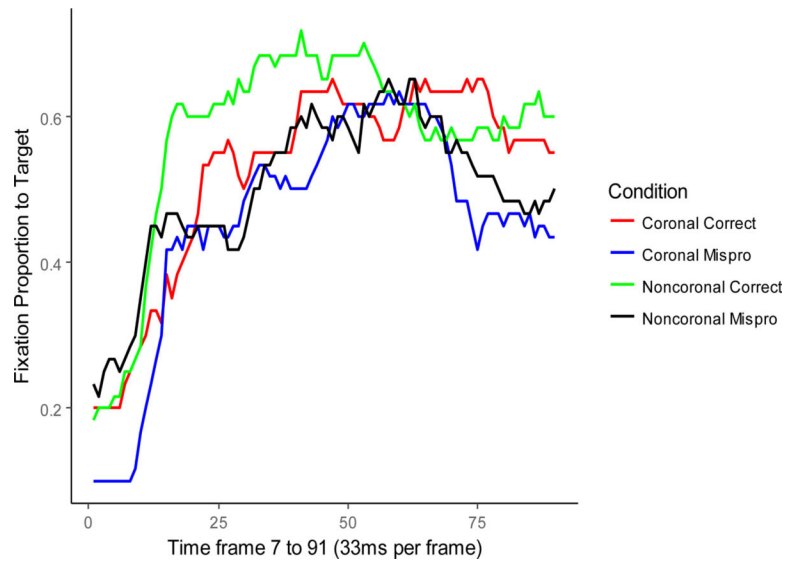


Figure 5. Experiment 1a: Time course data of toddlers' sensitivities to different directions of onset mispronunciations

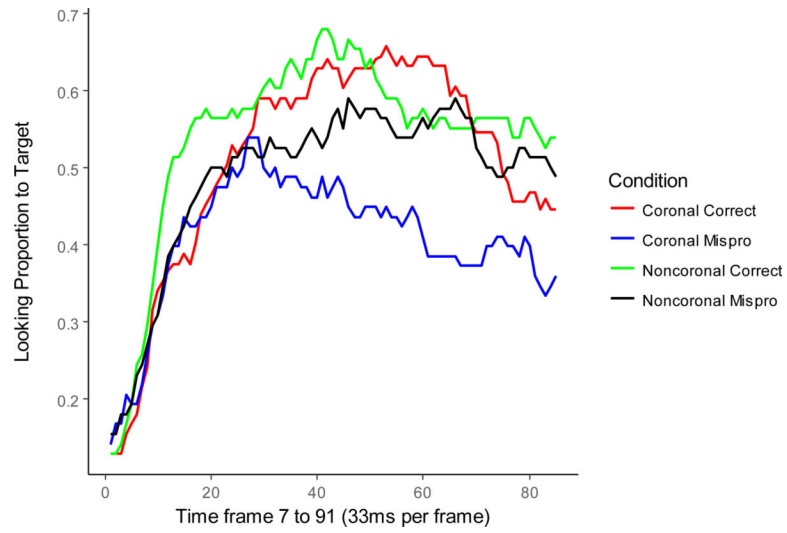


Figure 6. Experiment 1b: Time course data of toddlers' sensitivities to different directions of coda mispronunciations



Figure 7.
Sample visual stimulus pair in Experiments 2a & 2b.

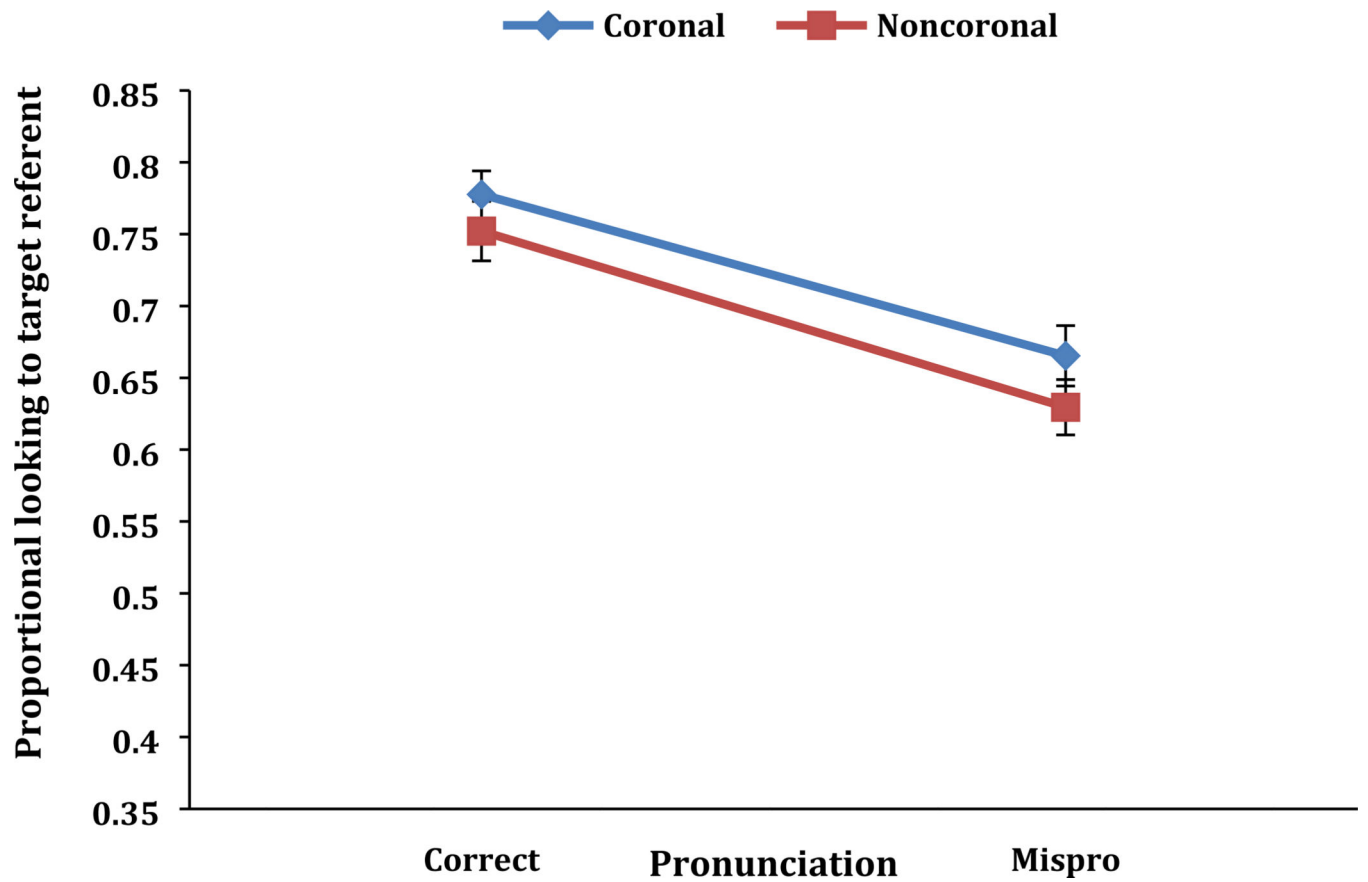


Figure 8. Experiment 2a: Adults' sensitivities to different directions of onset mispronunciations. Error bars show two standard errors computed via subject-wise non-parametric bootstrap.

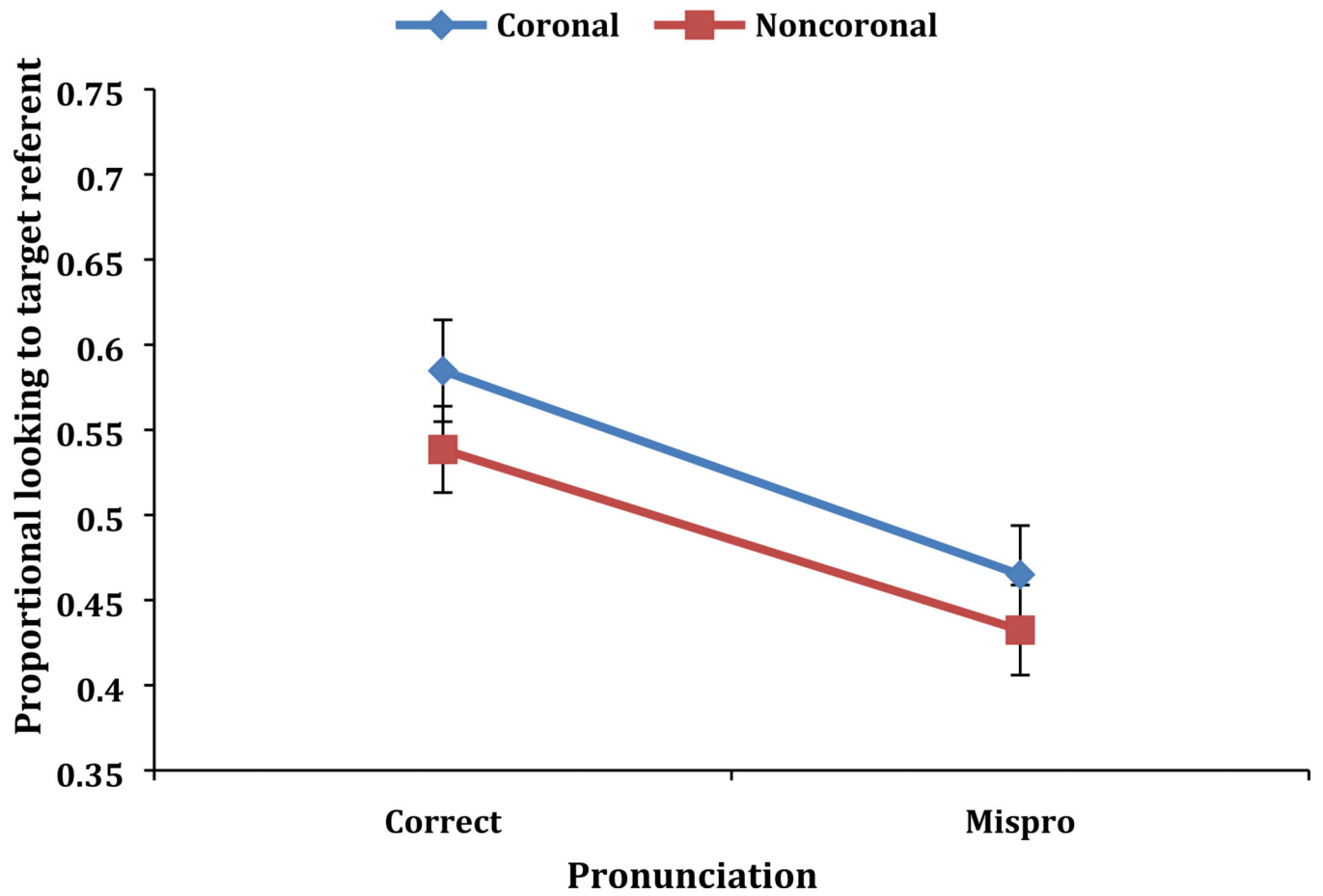


Figure 9. Experiment 2b: Adults' sensitivities to different directions of coda mispronunciations. Error bars show two standard errors computed via subject-wise non-parametric bootstrap.

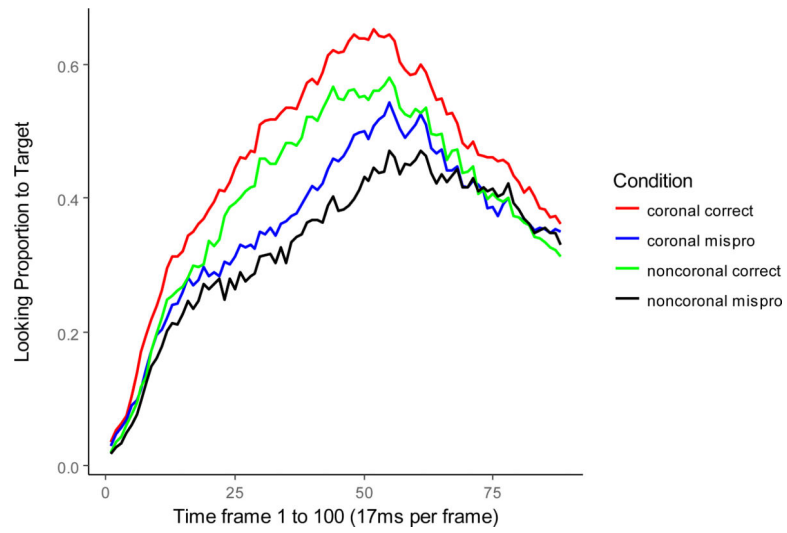


Figure 10. Experiment 2a: Time course data of adults' sensitivities to different directions of onset mispronunciations

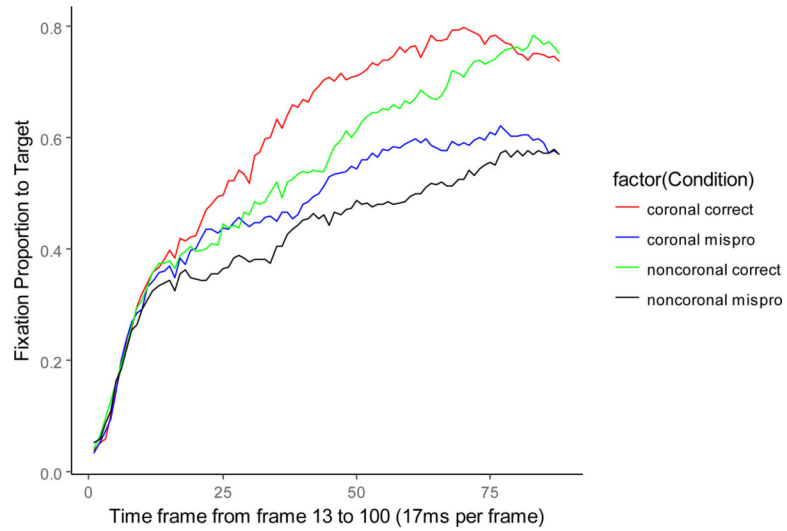


Figure 11. Experiment 2b: Time course data of adults' sensitivities to different directions of mispronunciations

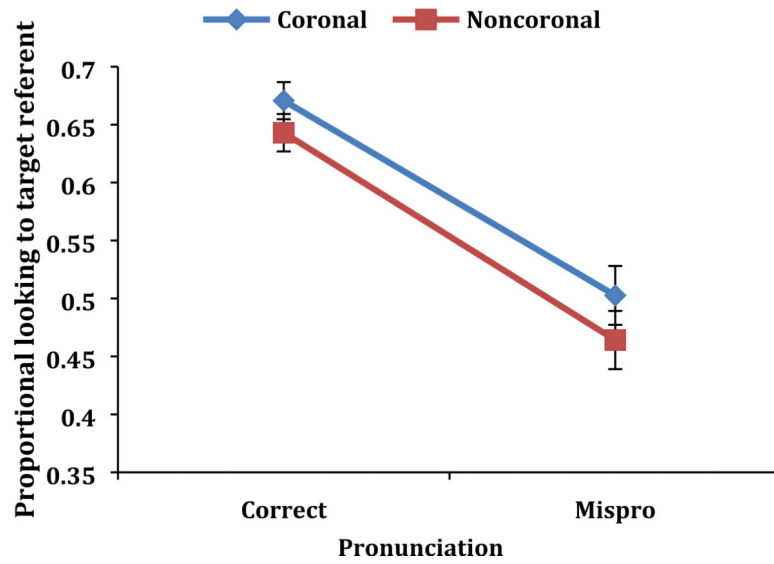


Figure 12. Adults' sensitivities to different directions of onset mispronunciations when the baseline phase is removed from the task. Error bars show two standard errors computed via subject-wise non-parametric bootstrap.

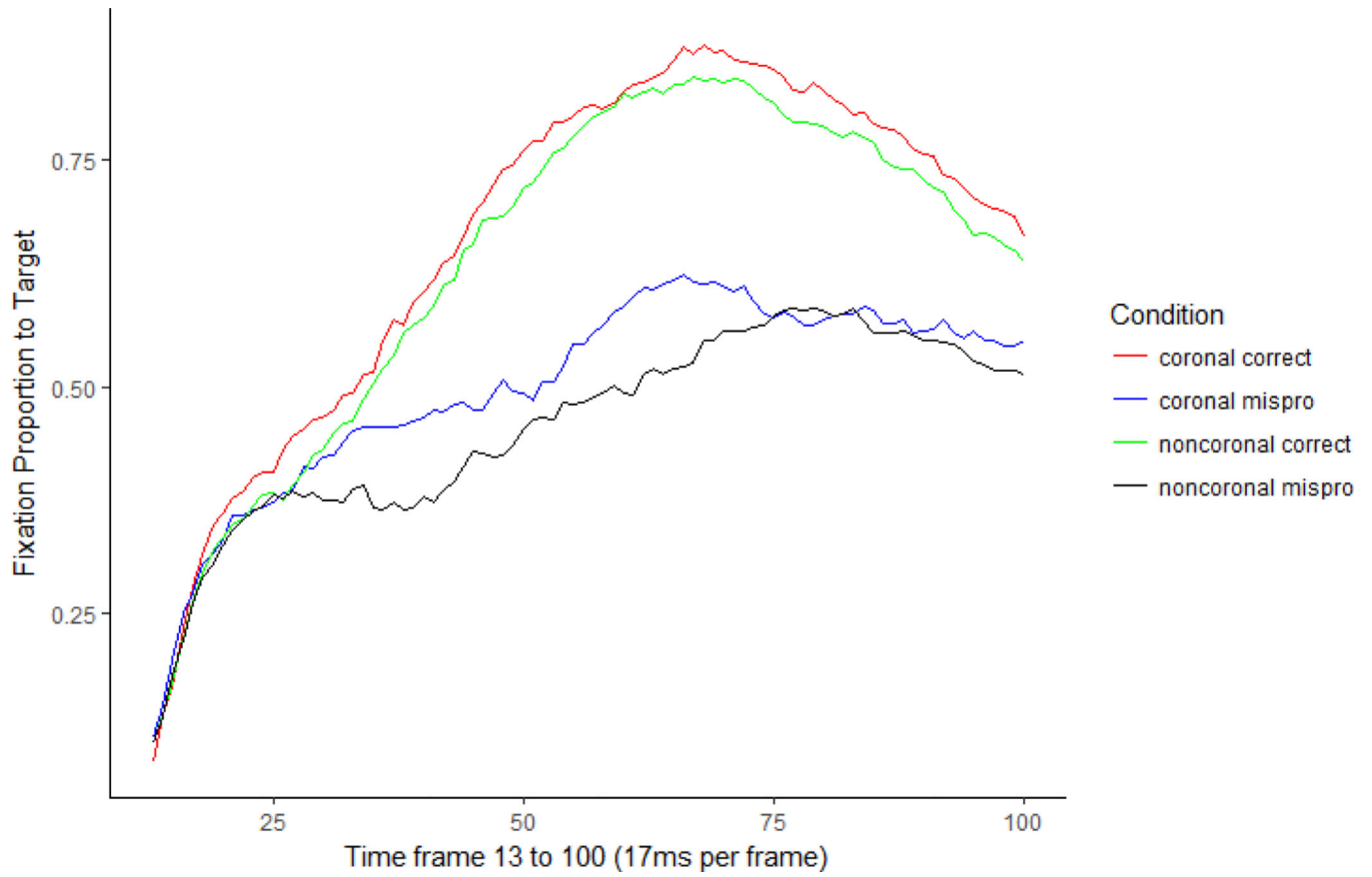


Figure 13. Time course of adults' sensitivities to different directions of onset mispronunciations when the baseline phase is removed from the task.

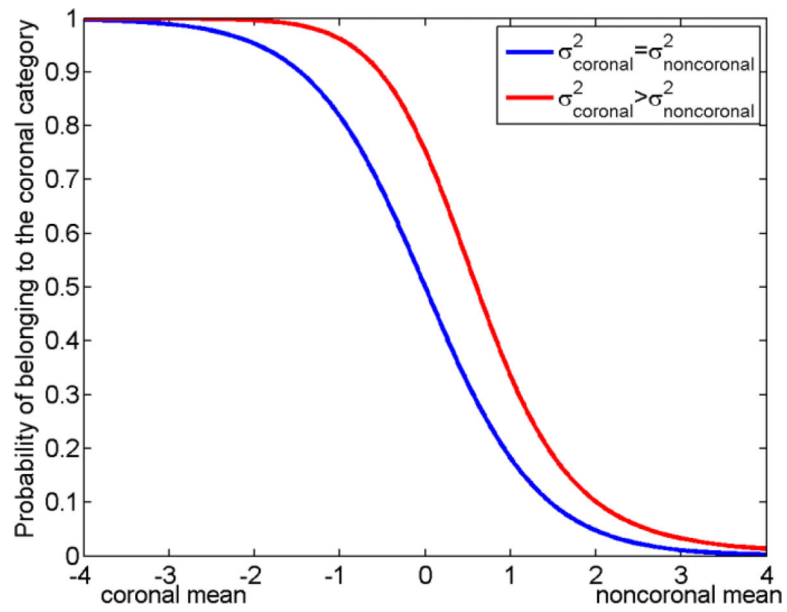


Figure 14. Simulation of category assignments under the assumption of Gaussian distribution with the variance of the broad category twice as the narrow category. Graph excerpted from Ren & Austerweil (2017).

Table 1

Sample stimuli for onset mispronunciations

Audio Stimuli Samples	(Mis)pronunciation	Place of articulation
<i>Where's the duck?</i>	Correct	Coronal
<i>Where's the guck?</i>	Mispronounced	Noncoronal
<i>Where's the cat?</i>	Correct	Noncoronal
<i>Where's the tat?</i>	Mispronounced	Coronal

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Table 2

Sample stimuli for coda mispronunciations

Audio Stimuli Samples ((Mis)pronunciation	Place of articulation
<i>Where's the cat?</i>	Correct	Coronal
<i>Where's the cak?</i>	Mispronounced	Noncoronal
<i>Where's the duck?</i>	Correct	Noncoronal
<i>Where's the dut?</i>	Mispronounced	Coronal

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Table 3

Posterior distributions of coefficients of Experiment 1a and 1b

<i>Coefficients</i>	Experiment 1a Infant Onset				Experiment 1b Infant Coda			
	<i>Mean</i>	<i>SD</i>	<i>95%</i>	<i>HDI</i>	<i>mean</i>	<i>SD</i>	<i>95%</i>	<i>HDI</i>
Intercept	-0.01	0.35	-0.68	0.68	-0.50	0.18	-0.85	-0.15
Time	0.69	0.14	0.42	0.97	0.96	0.08	0.81	1.11
Pronunciation	0.11	0.37	-0.62	0.84	0.68	0.16	0.37	0.99
Place of Articulation (POA)	0.02	0.45	-0.85	0.90	-0.28	0.20	-0.67	0.12
POA*Pronunciation	0.16	0.70	-1.22	1.54	-0.06	0.14	-0.32	0.21
Pronunciation*Time	0.22	0.26	-0.28	0.72	0.38	0.11	0.17	0.59
POA*Time	-0.13	0.18	-0.49	0.22	0.06	0.10	-0.13	0.26
POA*Pronunciation *Time	-0.01	0.27	-0.51	0.53	-0.07	0.11	-0.29	0.15

Table 4

Prior coefficients in Bayesian model comparisons

<i>Coefficient</i>	Model 1: Full-Specification	Model 2: Underspecification
Intercept	-3.440e-01	-5.306e-01
Time	7.344e-01	1.396e+00
Pronunciation	8.746e-01	3.036e-13
Place of Articulation (POA)	-1.447e-14	-8.746e-01
POA*Pronunciation	1.750e-14	8.746e-01
Pronunciation*Time	6.620e-01	1.055e-14
POA*Time	-8.674e-15	-6.620e-01
POA*Pronunciation *Time	1.016e-14	6.620e-01

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Table 5

Posterior distributions of coefficients of Experiment 2a and 2b

<i>Coefficients</i>	Experiment 2a Adult Onset				Experiment 2b Adult Coda			
	<i>mean</i>	<i>SD</i>	<i>95%</i>	<i>HDI</i>	<i>mean</i>	<i>SD</i>	<i>95%</i>	<i>HDI</i>
Intercept	-0.39	0.16	-0.69	-0.08	-0.50	0.18	-0.85	-0.15
Time	0.39	0.17	0.06	0.72	0.96	0.08	0.81	1.11
Pronunciation	0.58	0.22	0.16	1.00	0.68	0.16	0.37	0.99
Place of Articulation (POA)	-0.21	0.14	-0.47	0.06	-0.28	0.20	-0.67	0.12
POA*Pronunciation	0.03	0.30	-0.56	0.59	-0.06	0.14	-0.32	0.21
Pronunciation*Time	0.50	0.17	0.16	0.83	0.38	0.11	0.17	0.59
POA*Time	0.22	0.19	-0.16	0.62	0.06	0.10	-0.13	0.26
POA*Pronunciation *Time	-0.27	0.24	-0.74	0.20	-0.07	0.11	-0.29	0.15

Table 6

Posterior distributions of coefficients of Experiment 3

<i>Coefficient</i>	<i>Mean</i>	<i>SD</i>	<i>95%</i>	<i>HDI</i>
Intercept	-0.26	0.18	-0.60	0.09
Time	0.45	0.10	0.25	0.64
Pronunciation	0.72	0.13	0.48	1.00
Place of Articulation (POA)	-0.11	0.13	-0.37	0.15
POA*Pronunciation	0.02	0.13	-0.23	0.28
Pronunciation*Time	0.54	0.11	0.33	0.75
POA*Time	-0.02	0.05	-0.12	0.08
POA*Pronunciation *Time	0.01	0.03	-0.06	0.07

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Table 7

Frequencies of segments in CALLHOME transcripts by place of articulation

Language	Segments	Labial	Coronal	Velar
Arabic	All consonants	91,409	222,774	94,624
	Stops	25,592	54,279	38,544
Japanese	All consonants	57,513	236,813	99,760
	Stops	15,854	62,241	79,117
Spanish	All consonants	101,717	320,167	53,483
	Stops	44,366	62,961	43,005

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