Journal of Experimental Psychology:
Learning, Memory, and Cognition

ISSN: 0278-7393

2024, Vol. 50, No. 12, 1932–1953
https://doi.org/10.1037/xlm0001367

Coronal Underspecification as an Emerging Property in the Development of Speech Processing

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Is the developing lexicon phonologically detailed or are representations underspecified? Experimental results from toddlers suggest phonological specificity. By contrast, the featurally underspecified lexicon theory (Lahiri, 2018; Lahiri & Reetz, 2010), motivated by evidence such as the cross-linguistic prevalence of phenomena such as coronal assimilation (rainbow → rai[m]bow), proposes that coronal sounds are unspecified for place of articulation even in the adult lexicon. The featurally underspecified lexicon, therefore, predicts that asymmetries in mispronunciation sensitivity are also present in the developing lexicon. Recent research (Ren et al., 2019) has rejected this, reporting similar sensitivity to mispronunciation of coronals and noncoronals at 19 months. Using a more sensitive experimental paradigm, we provide new evidence demonstrating a lack of asymmetries at 18 months, but mispronunciation sensitivity for coronals disappears by 24 months. In an intermodal preferential looking study, growth curve analysis shows that 18-month-olds are sensitive to mispronunciations of words with a coronal (e.g., *duck* vs. **buck*) and noncoronal (e.g., *bird* vs. **dird*) onset. At 24 months, mispronunciations of coronal-onset words were treated just like the accurate pronunciations. We conclude that coronals are underspecified in the developing lexicon at 24 months. We propose a model under which initial representations are phonetic in nature and require exact acoustic input, whereas phonological coronal underspecification at the lexical level emerges gradually as a result of exposure to variation in the input such as coronal assimilations that only become detectable patterns with growing lexical and segmentation skills.

Keywords: mispronunciation sensitivity, phonological specificity, phonological development, eye tracking

Supplemental materials: https://doi.org/10.1037/xlm0001367.supp

In order to process speech reliably, children have to fulfill two basic requirements during language acquisition: (a) processing must be precise and (b) processing must be robust. All languages contain phonemes that are minimally discriminable, such as /n/ versus /m/, /p/ versus /b/, and /t/ versus /s/, each pair sharing many features but differing on a single dimension (e.g., place of articulation for /n/, /m/; voice for /b/ versus /p/, friction for /t/ versus /s/). There are minimal pairs, such as [deɪ] versus [beɪ] (*day* vs. *bay*), at the lexical level,

This article was published Online First July 29, 2024.
L. Robert Slevc served as action editor.
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The stimuli, data, and code relating to this article are available on the Open Science Framework and can be accessed at https://osf.io/5d2wr/, and the study was not preregistered. The authors have no conflicts of interest to disclose. This research was funded by a John Fell Grant (University of Oxford) to Aditi Lahiri and Kim Plunkett, by the EPSRC (Grant EPSRC EP/X026035/1, personal investigator: Aditi Lahiri) and the ESRC (Grant CQR01830, personal investigator: Kim Plunkett and Nuria Sebastian-Galles), and by the Winkler Fellowship in Experimental Psychology (St Hugh's College, University of Oxford) to Nadja Althaus. The authors thank the parents and children who participated in this study. The authors also thank Irina Lepădatu for the assistance with testing and Amanda Griffin for recording the speech stimuli.

Nadja Althaus played a lead role in data curation, formal analysis, investigation, methodology, visualization, writing–original draft, and writing–review and editing and an equal role in conceptualization. Aditi Lahiri played a lead role in funding acquisition and an equal role in conceptualization, investigation, methodology, project administration, writing–original draft, and writing–review and editing. Kim Plunkett played a lead role in funding acquisition and resources and an equal role in conceptualization, investigation, methodology, project administration, and writing–review and editing.
The data are available at https://osf.io/5d2wr/.
The experimental materials are available at https://osf.io/5d2wr/.
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which need to be discriminated very precisely in order to perceive speech accurately. However, the acoustic speech signal is highly variable: no two utterances, even of the same words by the same speaker, can ever be physically identical. In other words, the speech processing system also needs to be robust to variability. Spoken language invariably contains phonological processes such as assimilation, which result in systematic variation across occurrences of the same word depending on context. For example, the final consonant of *rain* [rɛɪn] is realized differently depending on the onset consonant of the following word:

1. raindrop → [reɪndrɔp]
2. rainbow → [reɪmboʊ]
3. raincoat → [reɪŋkoʊt]

The place of articulation of the coronal sound /n/ shifts to anticipate the place of articulation of the following consonant. Note that not all phonemes undergo such processes. The corresponding noncoronal /m/ does not change in the same contexts:

4. dream team → [dri:m ti:m], *[dri:n ti:m]
5. dreamboat → [dri:mboʊt]
6. dream coat → [dri:m koʊt], *[dri:ŋ koʊt]

In fact, across English, as well as other languages, it appears to be coronal sounds in particular that are subject to place assimilation, whereas noncoronal sounds are not affected. The question arises as to how the mental lexicon deals with this variability, which is after all not random but highly predictable. Indeed, there is even evidence from medieval manuscripts that when writing was less prescriptive, the orthography of words with sequences of [CORONAL] + [LABIAL] was variable (e.g., spellings "impatient" and "inpatient" can be found in the same manuscript copied by different scribes[1]). This is especially interesting during development, as infants must extract the phoneme inventory required for their language from the distribution of sounds in the language input they receive. Here, we ask how the developing mental lexicon represents these sounds. To illustrate, sampling different occurrences of the word "rain" will expose a child to [rɛɪn], as in "the rain stopped," to [rɛɪm] as in "rainbow" or [reɪŋ] in "raincoat" or "when the rain comes." The corresponding noncoronal sound /m/ will, by contrast, not show this kind of variability but always be realized as [m]. The same holds for other coronal/noncoronal pairings (/d/, /b/ and /b/, /p/). The question is whether this asymmetry is reflected in the lexical entry and in particular at what stage the developing lexicon represents these differences.

Some models of speech recognition assume that variability is handled by storing all possible variants, that is, every token that has been experienced is incorporated in the mental representation of the corresponding lexical entry (Coleman & Pierrehumbert, 1997; Pierrehumbert, 2001; Ettlinger & Johnson, 2009). Other models assume abstract representations, where variants are not necessarily stored (e.g., Connine et al., 1993; Cornell et al., 2011; Lahiri & Marslen-Wilson, 1991, 1992; Lahiri & Reetz, 2010; Wheeldon & Waksler, 2004). In particular, one theory is that mental representations of some phonemes such as coronal sounds do not specify their place feature at all but are *underspecified* (Kiparsky, 1982; Lahiri & Reetz, 2010). So, while a lexical entry for a noncoronal specifies the manner of articulation, voicing, and place of articulation (e.g., /p/ is represented as "manner: [PLOSIVE], voicing: [−VOICE], place: [LABIAL]"), a coronal sound is represented without the place feature (e.g., /t/ is represented as "manner: [PLOSIVE], voicing: [−VOICE], place: ∅"). These representations reflect what the features the lexicon *requires* to be present in the acoustic signal in order for the lexical entry to be activated. The implication of an underspecified representation is therefore that a *variety* of physical signals can activate a lexical entry—all those that match the remaining features that are specified. With an underspecified coronal-onset sound, a lexical entry like "tiger" (which is represented, as above: "manner: [PLOSIVE], voicing: [−VOICE], place: ∅") can be activated by [tiger] but also by * [piger] or *[kiger]. The reason for this is that the onset sounds [p] and [k] come with the relevant acoustic signals that match the required manner and voicing features, and as the lexical entry does not specify a place of articulation, the acoustic input cannot mismatch with the lexicon on that feature. Whether such featurally underspecified representations are present in the developing lexicon, that is, whether infants' responses to mispronunciations are compatible with lexical entries that do not contain a [CORONAL] feature, is what we investigate in the present work.

There is a large body of empirical results supporting the idea of coronal underspecification in adults. We review this literature in detail below. However, the developmental question is that of how words first enter the mental lexicon—is there evidence for underspecification for coronals early on, and does this change over development? This is a complex question given that young infants are still in the process of consolidating a phoneme inventory for their native language.

The question of whether infants' early lexical entries are detailed and represent all phonological features has also been investigated heavily, as we shall see below, although "underspecification" here is often treated in a broader way as representing some, but not all, detail of the exact phonological form (e.g., Jusczyk, 1993). Early work on encoding specificity mostly considered phonemes as holistic elements in this context (e.g., Stager & Werker, 1997). However, recent research has mostly dealt with sensitivity to mispronunciations at the level of phonological features (e.g., Mani & Plunkett, 2011; Tamási et al., 2017; White & Morgan, 2008, for work distinguishing 1-, 2-, and 3-feature mispronunciations).

Infants' phonological representations change considerably across the first year of life. Werker and colleagues (Werker et al., 1981; Werker & Tees, 1984) established that very young infants even discriminate sounds that do not occur in the language they hear, such as the Hindi retroflex/dental contrast /ʈa/-/t̪a/. This means that they can perceive at least some acoustic differences that distinguish these consonants. However, by 8–10 months, this ability atrophies, as infants "tune in" to their native language. By 12 months, infants hearing English no longer perceive the nonnative contrasts, whereas infants regularly exposed to the patterns do.

[1] 1. Chaucer, Geoffrey. The Tale of Melibee," MS Peniarth MS 392D, f. 225r, National Library of Wales Digital Gallery. https://www.library.wales/discover-learn/digital-exhibitions/manuscripts/the-middle-ages/the-hengwrt-chaucer. 2. "early 15th century, ca 1420-40:" Chaucer, Geoffrey. 'The Tale of Melibee," MS Petworth 486026, f. 242v, University of Manchester Library Image Collections. https://luna.manchester.ac.uk/luna/servlet/detail/Man4MedievalVC~4~4~569094~120789:Tale-of-Melibeus.

Concerning the coronal/noncoronal discrimination, there is particular controversy. Tsuji et al. (2015) conducted a discrimination experiment with Japanese and Dutch 4-month-olds in which they showed that there is an asymmetry. Habituated to a noncoronal sound sequence (repetitions of "ompa") and tested on a coronal one ("onta"), infants showed dishabituation, indicating that "onta" was not a good match when expecting a noncoronal. If habituated to the coronal sequence, by contrast, infants showed no dishabituation when hearing the noncoronal test. This suggests that the noncoronal is an acceptable match for an expected coronal—exactly what would be predicted by underspecification of the place feature, as indicated in the example above. It seems that even in the early stages of phonological development an asymmetry has been established. By contrast, results from familiar word recognition in 19-month-olds (Ren et al., 2019) did not reveal an asymmetry, suggesting that Tsuji et al.'s early asymmetries, which are found at a time when infants are barely beginning to learn their first words (Bortfeld et al., 2005; Tincoff & Jusczyk, 1999; although see Bergelson & Swingley, 2012, for evidence of word recognition at 6 months), do not play a role as the lexicon develops.

In the present article, we examine whether coronal/noncoronal asymmetries exist in somewhat older children, at 18 and 24 months, asking, on the one hand, whether Ren et al.'s study was sensitive enough to tap into these subtle differences in phonological processing and investigating a wider age range, on the other hand. At 18 months, the construction of the mental lexicon is well under way, and children enter the so-called vocabulary spurt, and by 24 months many children are proficient word learners. As we shall see, our studies show a developmental trajectory under which mispronunciation sensitivity is symmetrical at 18 months (i.e., infants are sensitive to all mispronunciations) but not at 24 months (i.e., infants do not show sensitivity to mispronunciations of coronals) in an intermodal preferential looking task. We will discuss the theoretical implications and how these findings, which at first sight appear contradictory to previous findings, in fact fit a pattern of emerging lexical representations that have their roots in early acoustic biases but are in a crucial way shaped by distributional information in the input that is only discoverable over time.

The Broad View of Underspecification in Developing Lexical Representation

As discussed above, some researchers hypothesized that initial entries might encode just as much detail as is necessary to discriminate all entries in the lexicon—which is initially restricted, as not many entries are known (Charles-Luce & Luce, 1990; Fikkert & Levelt, 2008; Jusczyk, 1993; Metsala, 1999).

In particular, this view of "underspecification" captures a rather broad idea about lexical representations which lack detail at earlier stages in development but will become more refined later on. It therefore does not capture the same idea as coronal underspecification in the featurally underspecified lexicon (FUL) model, which is concerned with the very specific phenomenon of lexical entries not containing a place-of-articulation feature for coronal consonants and the consequences thereof. Here, we first review research adopting the "broad view" of underspecification in the developing lexicon, before turning to previous work assuming the FUL model.

The broad view of underspecification came into particular focus after Stager and Werker (1997) found that infants at 14 months struggled to map two similar-sounding words (bih/dih) onto two different objects in a switch task, in which looking time for a word–object pairing consistent with familiarization is compared to looking time at a "switched" pairing. That same phonetic contrast was discriminated in an auditory-only task (Stager & Werker, 1997), and 14-month-olds were shown to perform well on the switch task with familiar words (Fennell & Werker, 2003). Later work found that more sensitive testing methods were able to demonstrate that infants in fact did show evidence of learning (Yoshida et al., 2009). However, infants' difficulties with similar-sounding words were also found in other contexts. For example, Swingley and Aslin (2007) showed that 18-month-olds struggle to learn words that are phonologically similar to existing lexical entries, for example, learning phonological neighbors such as "tog" [tɔg] or "gall" [gɔːl] for a new visual item is hard when "dog" and "ball" are known items, compared to learning novel nonneighbors. Even 24- to 30-month-olds, while noticing the difference between an accurately pronounced and a mispronounced familiar word (e.g., [tɔg] instead of [dɔg]), assume that a 1-segment mispronunciation refers to the familiar item (i.e., here, *dog*) rather than a novel object (Swingley, 2016).

Evidence for underspecification in familiar words, however, has been elusive. Swingley and Aslin (2000) showed that 18- and 24-month-olds had clear mispronunciation effects when presented with a word recognition study in an intermodal preferential looking paradigm (Golinkoff et al., 1987). Bailey and Plunkett (2002) similarly demonstrated sensitivity to mispronunciation in that age group, specifically highlighting that there were no age of acquisition effects (also see Swingley & Aslin, 2002; Zesiger et al., 2012). Ballem and Plunkett (2005) further found mispronunciation effects even for novel words just learned in the laboratory once infants had received enough training.

Varying mispronunciations by the degree of featural overlap with the accurate lexical entry, White and Morgan (2008) demonstrated that 19-month-olds' word recognition was dependent on the degree of mispronunciation, that is, they exhibited a larger reduction of target looking for mispronunciations involving a higher number of features. Tamási et al. (2017) reported converging results in 30-month-olds using pupillometry: children's pupil dilation in response to onset-mispronounced items scaled with the number of features that differed from the correct item (e.g., *Buch* [buːx] "book" < [vuːx] < [fuːx] < [ʃuːx]). Similar results pointing to sensitivity to mispronunciation of vowels were also reported (e.g., Mani & Plunkett, 2007, 2011; but see Nazzi et al., 2016, for a review of results pointing to consonantal mispronunciations being more disruptive than vowel mispronunciations). A meta-analysis (Von Holzen & Bergmann, 2021) of 32 infant studies (including children up to the age of 30 months) investigating mispronunciation sensitivity concluded that, in general, infants are sensitive to mispronunciation. Even though participants tended to identify the target object in intermodal preferential looking trials despite mispronunciation, they showed a significant reduction in target looking, and this did not appear to be age dependent.

While the consensus across these papers is that even young children's lexical entries are detailed and they are sensitive to mispronunciations, studies usually assume that all phonemes and features are equal in terms of their representation (with the exception of the vowel/consonant distinction; Havy & Nazzi, 2009;

Nazzi et al., 2009, 2016), and there is therefore no particular focus on contrasting coronals with their noncoronal counterparts.

Mayor and Plunkett (2014) provided further insights into early word recognition from a different perspective. Using the TRACE model (McClelland & Elman, 1986), which was developed to simulate adult speech recognition, they set out to compare simulated word recognition on correct and mispronounced input with infants' mispronunciation sensitivity as reported across the literature. To model speech recognition early in development, the model's lexicon is adapted to reflect the infant lexicon at the relevant age (both in terms of content and word frequencies). One of the main factors influencing word recognition in TRACE is the competition between different lexical entries. Mayor and Plunkett found that TRACE could successfully simulate a range of results, such as the symmetrical impact of consonant versus vowel mispronunciation (Mani & Plunkett, 2007) and (with adjusted phoneme-to-word connection strengths and reduced inhibition) the graded sensitivity to mispronunciation of different degrees of severity that was reported by White and Morgan (2008), as well as Swingley and Aslin's effect of reduced target preference when learning novel words that are phonological neighbors of familiar words. The latter, however, is here explained as a mispronunciation effect on the target trial rather than a failure in word learning per se. The TRACE simulations demonstrate that many effects relating to mispronunciation sensitivity in the developing lexicon can be explained on the basis of the lexicon itself (which changes over time) rather than specific processes. In particular, the premise of the TRACE model is that all lexical entries are fully specified, so the fact that many of the results could be simulated with this setup implies that featural underspecification is not necessary to explain the experimental data that were investigated here. However, the asymmetry between coronal and noncoronal sounds that is the focus of the present work has not yet been investigated systematically with TRACE.

Coronal Underspecification

In the present study, we focus on just coronal/noncoronal contrasts between /n, d, t/ and their counterparts /m, b, p/. Based on alternations such as the assimilation examples above and a variety of other phenomena such as "coronal transparency," underspecification of the coronal feature was proposed in the 1980s and 1990s (cf. Archangeli, 1988; Paradis & Prunet, 1989; Steriade, 1995). The arguments were all based on phonological alternations. Lahiri and Reetz (2010) proposed the FUL, aiming to formalize the hypothesis of coronal underspecification in terms of language processing. FUL proposed among others a model of lexical access (cf. Lahiri, 2018, for recent coverage). The two features that were assumed to be always underspecified were [PLOSIVE] and [CORONAL] (cf. Cornell et al., 2013), but here we focus only on [CORONAL]. As explained above, underspecification of [CORONAL] implies that the lexical entry becomes robust to variation in the input with regard to this feature. The default place surface feature that is realized for a sound with an unspecified place feature is "coronal." In a context of neighboring coronal sounds (vocalic or other consonants such as /l r d t/), the coronal is realized; consequently, the /n/ in *rain* remains unaltered in *raindrop*, but in the context of noncoronal (e.g., dorsal or labial) consonants, the sound is assimilated (e.g., *raincoat* [reɪŋkoʊt], *rainbow* [reɪmboʊ]). Crucially, underspecification does not imply that the difference between coronals and noncoronals cannot be *perceived* from the acoustic input—the concept relates to activation and representation in the mental lexicon. Unlike the broad concept of "underspecification" in the language acquisition literature discussed in the previous section, which concerns a nonspecific lack of detail in the verbal encoding and therefore refers to a kind of developmental deficiency that is thought to disappear as development progresses, the linguistic theory behind coronal underspecification is motivated by alternations arising from phonological processes and found across many languages. The variants are present in the input to the child and remain in the signal throughout life. Under this theory, coronal underspecification is therefore a property of language in general and not an experience-dependent lack of precision that will disappear over time as lexical entries become more precise.

Thus far, our examples (such as *rainbow* [reɪmboʊ]) suggest assimilations at word boundaries. Since the assimilations involving place of articulation are in general regressive, they cannot affect initial consonants. Our theoretical position is, however, that the underspecification of the feature is not bound to any position within the word but rather that the place feature is unspecified for coronals in all positions (Lahiri, 2015, 2018). Although one of the main reasons for assuming underspecification of coronals has been the prominence of these regressive assimilations, the strongest *test* for an underspecified feature affecting a class of phonemes is to test mispronunciation sensitivity in the initial position (cf. Friedrich et al., 2008, for adult work on onset coronal mispronunciations).

A large part of the literature on coronal underspecification derives from the question of how the speech recognition system deals with rule-based variation, as found with place assimilation. Here, the critical point is whether the nature of the lexical entry itself takes care of variability in the input (either via storing multiple variants or by underspecifying the relevant phonemes) or whether this occurs in a separate process which is restricted to contexts in which assimilation takes place. Wheeldon and Waksler (2004), using a cross-modal repetition priming paradigm, reported that offset mispronunciations of coronals primed the accurate form (e.g., **wickib* primes *wicked*) regardless of whether the priming context was appropriate for assimilation (as in *a *wickib prince*) or not (*a *wickib ghost*). Gumnior et al. (2005) provided similar findings for German compound boundaries. The results reported in these studies are consistent with the theory that coronals are unspecified for place in the mental lexicon. However, word-medial phonemes have also been investigated, and this line of research provides further evidence for coronal underspecification independent of context. Friedrich et al. (2006) used event-related potentials (ERPs) to examine the neural basis of mispronunciation detection. They used pairs of accurately versus mispronounced German words with coronals or noncoronals in word-medial position (e.g., Probe/*Prode, Horde/*Horbe) to elicit an N400 effect. The N400 is observed for wordlike pseudowords (Kutas & Federmeier, 2000) and was used here in the context of a lexical decision task. All mispronunciations elicited an N400, but mispronounced noncoronals led to an earlier onset of the N400 component, indicating that coronal mispronunciations seemed acceptable as a word for a longer amount of time.

In a similar paradigm also aimed at the N400 pseudoword effect, Friedrich et al. (2008) examined word-initial mispronunciations in lexical decision as well as cross-modal fragment priming. Consistent with the earlier work on medial consonants, they found that mispronunciations of coronals (Drachen/*Brachen) still activated the target lexical entry effectively, whereas mispronunciations of noncoronals (Grenze/*Drenze) failed to do so. Finally, Roberts et al. (2013) combined behavioral and ERP data in a study of word-medial consonants in English, using stimulus pairs such as tenor/*temor and image/*inage to investigate the ability of mispronunciations to activate lexical entries. Their results reveal asymmetries in both reaction time and N400 and are, thus, in line with those by Friedrich and colleagues, supporting the FUL model.

Contrasting these findings, Mitterer (2011) conducted a series of visual world eye-tracking studies investigating coronals versus noncoronals and reported finding no evidence for asymmetries. However, since written words were used as visual items, orthographic competition between target and distracter items cannot be excluded.

There are approaches that attribute identified asymmetries between coronal and noncoronal items, not to the underlying featural representation but to the surface distribution of acoustic properties only. Ren and Austerweil (2017) present such an approach, using Bayesian models to demonstrate that asymmetries would be expected under circumstances where the acoustic sounds are more variable but also more frequent in a language.

However, the first aspect, variability, in fact speaks *for* underspecification of coronals rather than against it. A large part of the variability stems from assimilations, as discussed above. These, however, are governed by clear phonological rules. Cross-linguistically, there are more coronal variants than, for example, labial variants (e.g., English has 11 coronal [t, d, θ, ð, s, z, ʃ, ʒ, l, r, n] but five labial consonants [p, b, f, v, m]—the International Phonetic Alphabet lists 41 coronals and 16 labials). The shape of the mouth in making a coronal makes this class of sounds acoustically more robust than, for instance, labials. English /t/ or /s/ sounds, for example, have more high-frequency energy in the signal than their labial counterparts /p/ and /f/ (Jongman, 1989; Lahiri et al., 1984; Stevens & Blumstein, 1978).

The true frequency of coronals is more difficult to assess. They may not be more frequent in terms of occurrence in base forms in the lexicon (e.g., CELEX lists 259 monomorphemic monosyllables starting with /p/ and 214 starting with /t/ but 246 starting with /f/ and 623 with /s/; Baayen et al., 1996). However, it is a different picture once grammatical morphemes are taken into account—for example, in English all grammatical morphemes marking number or tense contain coronals (plurals ending in /z/ or /s/, past tense ending in /−d/ or /−t/). There is therefore an expected asymmetry in terms of frequency.

The Development of Coronal Underspecification

The development of coronal underspecification has also been considered by previous research. As briefly addressed above, there are two mechanisms that matter with regard to coronal underspecification. On the one hand, there are biases based on acoustic properties and articulation (i.e., the tongue being in neutral position for coronals but moved for other places of articulation). On the other hand, there is a statistical pattern of context-dependent alternations between different sounds present in the input. We would predict that children extract these alternations only over time as they become proficient in skills such as speech segmentation, which in itself is tied to lexical development. There are therefore two possibilities: either coronals are underspecified for place of articulation from the beginning of lexical development, or asymmetries develop only gradually with prolonged exposure to the distribution of coronals and alternations in the input.

Different paradigms have been used to investigate coronal underspecification and tap into different levels of representation, including studies on perceptual discrimination of nonwords, and recognition of recently learned words and familiar words (assumed to have been learned before the lab visit) in different age groups. There is evidence regarding differences in *perception* between coronals and noncoronals from early on in development. Dijkstra and Fikkert (2011) habituated 6-month-old Dutch infants with pseudowords "paan" or "taan" and tested preferential listening for either a sequence containing only repetitions of the familiar item or a sequence alternating between the coronal and labial pseudowords. They found that infants only showed a preference for the alternating sequence after habituation with "paan," not after habituation with "taan." This was interpreted as consistent with the idea of /t/, but not /p/, being unspecified for place of articulation. As already mentioned above, Tsuji et al. (2015) demonstrated that even younger infants at 4 months show this asymmetry in word-internal alternations ("ompa"/"onta") and, further, that it is not just found in infants hearing Germanic languages such as Dutch but also in infants hearing Japanese, for whom coronal stops are not the most frequent plosives. Van der Feest and Fikkert (2015) used a preferential looking paradigm with familiar words that were either pronounced correctly or mispronounced. Investigating 20- and 24-month-olds, they found consistent results in that both age groups were sensitive to mispronunciation of words with a labial onset, but not of those with a coronal onset. Altvater-Mackensen et al. (2014) reported a similar asymmetry for 18-month-olds in a preferential looking study with fricative onsets (e.g., *vis* "fish" mispronounced as *zis*). Tsuji et al. (2016) presented results on asymmetries in newly learned words with Japanese and Dutch toddlers. In their experiment, 18-month-olds learned two novel, coronal-onset words for two novel objects in a mixed live learning and screen-based learning procedure. They were then tested on word recognition for the accurate word form and for a dorsal or labial mispronunciation. While toddlers from both language groups were clearly sensitive to the coronal–dorsal mispronunciation, they showed a lower sensitivity to the labial mispronunciation, and this was particularly clear for the Dutch group. The authors argue that the sensitivity to dorsal mispronunciations is evidence against underspecification as the underlying cause of the lack of mispronunciation sensitivity for coronals, but they also point out that adult confusability data support the idea that a coronal-to-dorsal change is easier to perceive than a coronal-to-labial change. We would argue that this could be particularly relevant in a study that assesses newly learned words, for which we cannot, in fact, be sure that a lexical entry has been found (see, e.g., Bion et al., 2013; Horst & Samuelson, 2008, for evidence for a lack of retention for newly learned words even in 24-month-olds). It seems likely that preferential looking results may be based on a simpler representation that may not involve full phonological encoding and therefore be largely reliant on perceptual discrimination.

Until this point, then, it looks like there is a clear developmental picture with early asymmetries that are found in studies on perceptual discrimination of nonwords (as early as 4 months) and asymmetries in mispronunciation studies that involve referent recognition later on, when lexical development is under way (18 months onward). It is therefore plausible that early acoustic/perceptual asymmetries lead directly to underspecified lexical entries.

However, Ren et al. (2019) presented a contradictory looking time study with 19-month-olds as well as a corresponding adult study. They used a preferential looking paradigm in which each trial presented infants with both a familiar item and a novel item. Auditory stimuli contained either accurately pronounced or mispronounced versions of words with coronal versus noncoronal onsets (Experiment 1a) or codas (Experiment 1b). The rationale of this experiment was as follows: If infants notice the mispronunciation of the stimulus, that is, to them [gɔg] is not the same as [dɔg], then by the mutual exclusivity assumption, they should interpret that word as potentially referring to the second visual item and therefore move their eyes toward that item (White & Morgan, 2008). In this way, the method aimed to be more sensitive than traditional preferential looking tasks in which both items are familiar. In those tasks, the child knows that the second item is not the referent of the auditory stimulus. A mispronunciation might then be interpreted as an acceptable version of the word they know (e.g., [gɔg] would be perceived as a merely distorted version of [dɔg]) in the absence of a more suitable referent, and as a result, their looking behavior might not change, despite sensitivity to pronunciation accuracy.

Neither of Ren et al.'s (2019) studies identified asymmetries in infants' looking responses. The authors presented this as contradicting the previous work by Fikkert et al. and inconsistent with the adult work by Lahiri et al. The results are certainly inconsistent with a developmental trajectory in which early acoustic/perceptual biases give rise to lexical entries that are underspecified from the outset.

Another explanation, however, may be that the method used by Ren et al. (2019) was not sensitive enough to pick up on asymmetries in mispronunciation sensitivity. One misconception regarding the FUL model is that underspecification implies absolute insensitivity, that is, that mispronunciations cannot be perceived at all. By contrast, underspecification refers to the *phonological* level of representation rather than the *perceptual* one. Phonological representations of sounds such as /t/ and /p/ are more similar than /p/ and /k/ because the place feature is not specified for /t/. At the perceptual level, it is perfectly possible that the distinction is *heard*. The difference lies in the lexical activation that is at a higher level than perception itself.

To tap into such a fine-grained difference, then, a highly sensitive method is necessary. Ren et al.'s looking time studies used a "salience phase," a period of purely visual exposure to the two target images that preceded the intermodal preferential looking part of the trial itself. This was included in order to be able to compare looking preferences after naming with baseline preferential looking. While this is sensible in most preferential looking tasks and serves to exclude biases due to one of the items presented side by side being more visually interesting than the other, it is a disadvantage in mispronunciation studies. To explain this, let us briefly consider what processes we expect to occur during a trial with a target word and two visual images. The idea underlying intermodal preferential looking is that hearing the target word activates a lexical entry, and on this basis each of the visual images can either be matched or rejected as the referent. However, we know from Mani and Plunkett's (2010) study using picture priming that infants (at least by 18 months) already generate a label upon seeing the objects, that is, a lexical entry is activated as soon as a visual target is perceived. This is not a problem in a study that merely asks whether a child can recognize a word like "dog" to refer to the picture of a dog versus the picture of, say, a bird. But a mispronunciation study relies on the idea that the mispronounced auditory label should activate a lexical entry *to a lesser extent* than the accurate form (it is understood that even a mispronounced item will partially activate a lexical entry due to the remaining overlap of the target word and those parts of the word that are not mispronounced). During an initial silent phase like the one in Ren et al.'s study, children are likely to (mentally) generate labels for the objects they see, that is, in the present context only for the familiar item. By the time they hear the label, it is already too late to test whether the auditory stimulus is able to activate the lexical entry. The lexical entry has already been activated by the visual input alone, and the child has generated a phonological, possibly even phonetic, level representation. In this scenario it seems plausible that a mispronunciation may register as a suboptimal auditory form, but the discrepancy may not be interpreted as critical, even in the presence of a distracter object whose name is not known: The child expects to hear [dɔg] on the basis of seeing the picture—so hearing [gɔg] might not be so disruptive as to cause reinterpretation as a new lexical item that refers to the other object. After all, [gɔg] by design does not activate a competing lexical entry. Such a process is consistent with Swingley's (2016) study with 2-year-olds, who readily interpreted 1-segment mispronunciations as acceptable versions of known words. Even if small decrements in target looking can be found in this scenario, the method may not be sensitive enough to pick up on an asymmetry between mispronunciations of coronal versus noncoronal sounds—any discrepancy in activation levels is likely to be diluted by preactivation of the relevant lexical entry.

Another question is whether the development of coronal asymmetries can be captured by testing infants at this particular age group. While the FUL model is consistent with the idea that asymmetries arise early on in development, it is also possible that the way sensory processes and lexical activation interact changes as the child gains more experience with language.

In order to investigate coronal underspecification during development more closely and resolve the emerging contradiction between Ren et al.'s findings (no asymmetries found) versus those from Fikkert and others (asymmetries found), we conducted a study with two groups of infants, 18- and 24-month-olds, using a more sensitive paradigm that avoids the problem with Ren et al.'s "salience phase." We used a similar paradigm based on White and Morgan's trial design (i.e., one familiar and one novel item side by side). Unlike Ren et al.'s study, we presented auditory items—accurate or mispronounced—*before* the onset of the visual images, so that implicit naming of a visual stimulus is minimized, that is, a lexical item is not yet activated before the mispronunciation is heard. In order to avoid variability stemming from different sound classes being used (e.g., contrasting coronals with a mixture of both dorsal and labial sounds), we solely used labial items as noncoronal targets and used labial mispronunciations of coronal sounds.

The Current Experiments

In order to test the development of mispronunciation sensitivity, we conducted two sets of experiments with infants at 18 and 24 months as discussed. We used a paired preference paradigm in order to capture precise time course information of the processes involved. We followed White and Morgan's (2008) design in order to be able to capture fine-grained differences between gaze patterns for correct and mispronounced items: trials always contrasted one known item (e.g., tiger) with a novel object for which infants did not know a name. As described above, the logic of this design is that if a mispronunciation (e.g., "piger") is detected, children should be able to interpret this as a novel word and map it onto the novel item by mutual exclusivity (Halberda, 2003).

Method

The work in this experiment was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the Oxford University Medical Sciences Division Research Ethics Committee.

Transparency and Openness

We report how we determined our sample size, data exclusions, all manipulations, and all measures in the study. The stimuli, data, and analysis code are shared at https://osf.io/5d2wr/. Data were analyzed using R Version 4.2.2 (R Core Team, 2022), packages lme4 (Bates et al., 2015) and multcomp (Hothorn et al., 2008). The study's design and its analysis were not preregistered.

Participants

Two groups of infants took part in this study, one group of 18-month-olds (N = 20, M_{age}: 18.41 months, range: 17.97–18.69 months, 10 girls) and one group of 24-month-olds (N = 25, M_{age}: 24.24 months, range: 23.69–25.10, nine girls). Fifteen additional infants (six 18-month-olds and nine 24-month-olds) were tested but excluded from the analysis due to fussing (N = 7), technical issues (N = 1), missing Communicative Development Inventory (CDI) data (N = 3), and low overall target preference on correct trials (N = 4; <2 SD below mean). Sample sizes were determined on the basis of previous research using similar methods (Ren et al., 2019; Tsuji et al., 2016; White & Morgan, 2008). All heard English as their main language at home. Participants' caregivers were contacted after having previously indicated their interest in study participation, typically at a researcher's visit to the local maternity ward.

Stimuli

Target Items

We used a total of 16 familiar visual items as the target stimuli. These were selected to be items that at least 50% of 18-month-olds understand, according to the lab's extensive Oxford CDI database (Hamilton et al., 2000). Eight items started with a coronal sound and eight with a noncoronal. The coronals and noncoronals were approximately matched with regard to the other onset sound features. The full list of items is provided in Table 1 (see Figure 1, e.g., stimuli). Targets were chosen such that the number of animates was the same across both sets (not counting nose as animate, there were three animate coronals and three animate noncoronals), the average Childes log frequencies were similar, $t(14) = 0.4$, $p > .69$, two-sample t test coronals versus noncoronals, and the average proportions of infants at 18 months who understand the item were similar, $t(14) = 0.17$, $p > .86$. Due to the low number of words suitable for this task (in addition to the aforementioned criteria, items needed to be imageable and mispronunciations could not be an existing word), we selected three items from the /d/ cohort but five items from the /b/ cohort, three items from the /t/ cohort and two from the /p/ cohort, and two items from the /n/ cohort and just one item from the /m/ cohort.

For each item, a color photograph was prepared using the *GIMP* photoediting software (Gnu Image Manipulation Program, 2022) and placed on a 50% gray background. Care was taken to ensure that individual images appeared approximately equal in size and color saturation.

Distracter Items

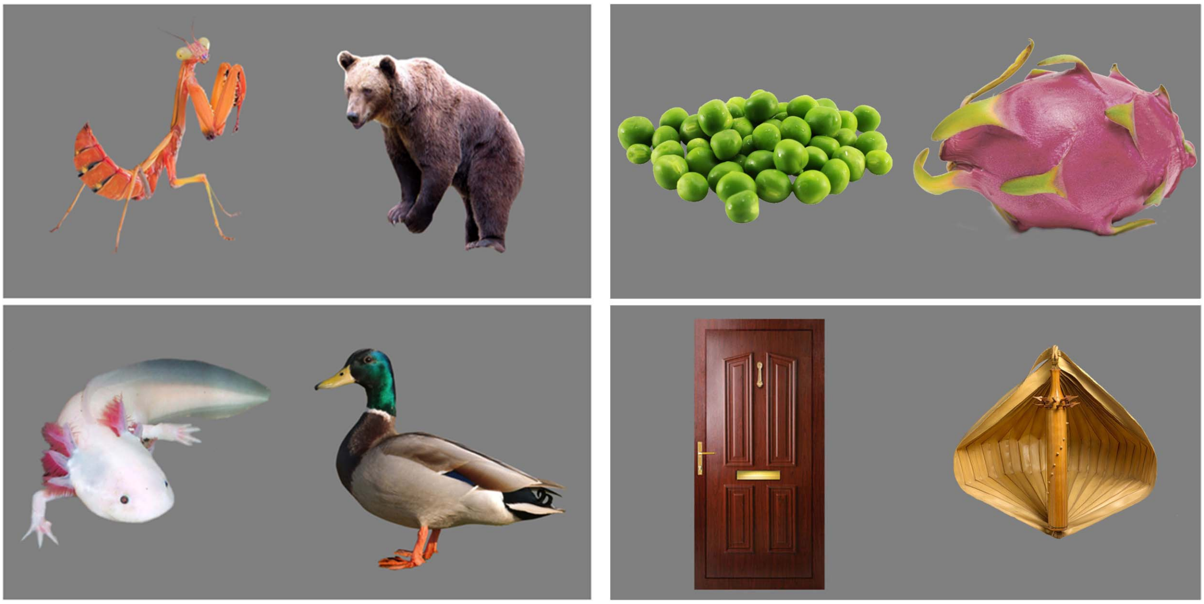
For each target item, we selected a novel object to appear alongside it as an unknown distracter. In order to minimize the difference in saliency, distracters for animate objects were also animate (e.g., armadillo was paired with dog, flying squirrel paired with tiger, chameleon paired with pig), and distracters for inanimates were inanimate. Photographs of unknown items were prepared the same

Table 1
Target Items for Experiment 1

Target	Known @ 18	Known @ 24	Childes LogF	No. of neighbors	Condition	Mispronounced
dog [dɒg]	0.97	0.98	2.77	19	C	[bɒg]
duck [dʌk]	0.92	0.98	2.37	31	C	[bʌk]
door [dɔ:]	0.84	0.97	2.72	3	C	[bɔ:]
tiger [tʌɪgə]	0.54	0.87	2.61	2	C	[pʌɪgə]
table [teɪbl]	0.64	0.94	2.73	10	C	[peɪbl]
towel [taʊəl]	0.53	0.89	1.72	4	C	[paʊəl]
nappy [napi]	0.92	0.98	1.43	2	C	[mapi]
nose [nəʊz]	0.91	0.98	2.54	9	C	[məʊz]
bird [bə:d]	0.83	0.98	2.45	16	NC	[də:d]
bear [bɛ:]	0.55	0.88	2.3	24	NC	[dɛ:]
book [bʊk]	0.97	0.99	2.94	18	NC	[dʊk]
pig [pɪg]	0.77	0.96	2.19	20	NC	[tɪg]
boat [bəʊt]	0.63	0.95	2.27	23	NC	[dəʊt]
peas [pi:z]	0.55	0.89	1.52		NC	[ti:z]
bath [bɑ:θ]	0.95	0.98	1.71		NC	[dɑ:θ]
milk [mɪlk]	0.9	0.98	2.72	14	NC	[nɪlk]

Note. Known @ 18/24 refers to the proportion of 18-/24-month-old infants in the Oxford Communicative Development Inventory database whose caregivers indicated that the child "understands" the word in question. Condition: C = coronal; NC = noncoronal.

Figure 1
Example Stimuli



Note. Pairs of stimuli were yoked across conditions so that the same familiar and novel items were shown together, regardless of whether the auditory item was correct, mispronounced, or novel (these images are to illustrate sample pairings; on screen there was more space between and around the items). See the online article for the color version of this figure.

way as the target items. Care was taken to ensure that the overall "interestingness" of target and distracter was approximately equal, for example, brightly colored peas were paired with a picture of a dragon fruit that was deemed of similar visual saliency. For example stimuli and pairings, see Figure 1.

Auditory Stimuli

All target items, mispronunciations, and 16 novel words were recorded in a sound-attenuated booth with a female native speaker of British English using a child-directed tone of voice. Mispronunciations involved a one-feature change, either from a coronal to a noncoronal (e.g., *dog* [dɒg] to [bɒg]) or vice versa (e.g., *boat* [bəʊt] to [dəʊt]). For a full list of targets and mispronunciations, see Table 1. Novel words were constructed such that they had the same onset sounds as used in the targets/mispronunciations, and the distribution of monosyllables/disyllables was kept the same (examples included "marlet," "panker," "dage," "torper," "bink"). Auditory stimuli were spliced and padded with silence using Audacity.

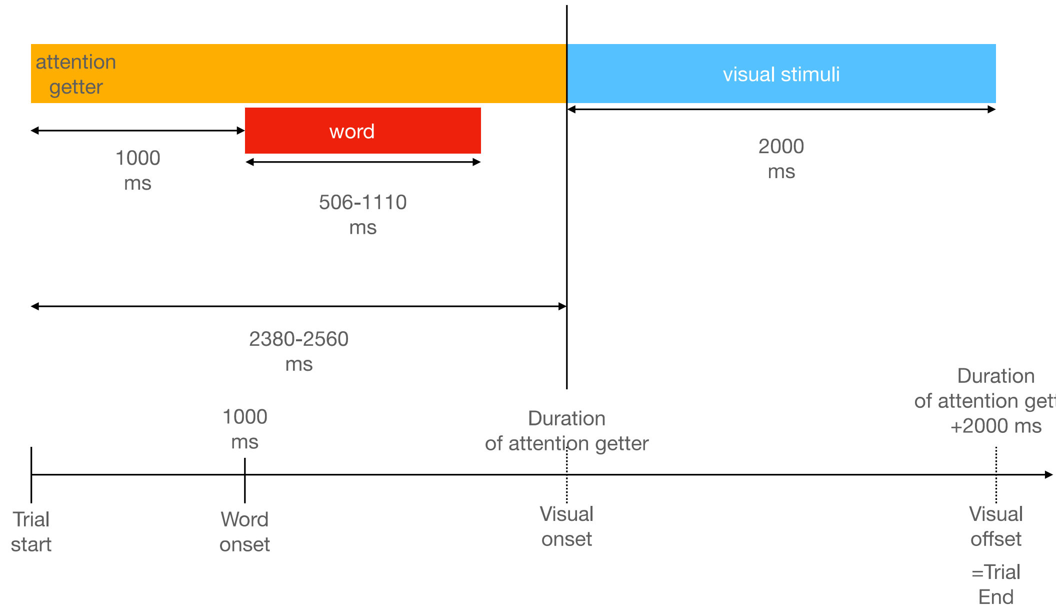
Design

The experiment was designed as a within-subjects procedure. Subjects saw three blocks of trials with each visual pair occurring once per block. One of these occurrences was presented with accurate target pronunciation, one with target mispronunciation, and one with a novel word. Novel word trials were included as fillers to avoid participants learning that the familiar item was always the named item, which could otherwise over time affect looking behavior. The pairing of visual and auditory stimuli was carefully balanced so that each child saw approximately equal numbers of correct/mispronounced/novel items per block, and across subjects the temporal order of correct/mispronounced/novel auditory stimulus for each visual pair was counterbalanced (i.e., dog/armadillo with correct pronunciation occurred equally often in Block 1 as it did in Block 2 and 3, across subjects).

Procedure

Prior to the lab visit, caregivers filled in an online version of the Oxford CDI (Hamilton et al., 2000). Caregivers and children were welcomed in the lab's reception, where the procedure was explained to the caregiver and written consent was obtained. Enough time was taken to allow the toddler to settle in and become familiar with the experimenter. After this, the caregiver and the child were accompanied to a testing booth where the child was seated on the caregiver's lap, approximately 60 cm from the eye tracker and screen. After the chair and eye tracker were adjusted for height, curtains were closed behind the participant, and a 5-point calibration procedure was conducted. A rotating yellow star on 50% gray background with accompanying sounds was used to attract attention to the calibration points. The calibration procedure was repeated until all 5 points were calibrated successfully. After this, the participant was presented with the 48 trials as described above. Before each trial, a blue dot was shown at the center of the screen to encourage fixation to this point. After ensuring that the child was looking at the screen, the experimenter triggered the start of a trial. The trial timeline is illustrated in Figure 2. Each trial began with an animation video (simple, moving geometrical shapes at the center of the screen) to attract attention to the center. After 1 s, the auditory label was presented in a child-directed voice. Pictures (familiar and novel items) appeared on average at 2.48 s after trial onset, with a

Figure 2
Trial Timeline



Note. See the online article for the color version of this figure.

jitter, which was introduced in order to avoid infants falling into a pattern of anticipating picture onset (M = 2.48 s, min = 2.38 ms, max = 2.56 ms). Picture offset was always at 2 s after picture onset. Eye movements were recorded by a Tobii TX300 sampling at 120 Hz throughout the procedure. Custom Matlab scripts were used for stimulus presentation and logging.

Results

As infants begin each trial by landing a fixation either on the familiar or the novel item, there are two types of trials—familiar-first (FF) trials and novel-first (NF) trials. As reported in other, similar preferential looking paradigms, these unfold in different ways (e.g., Fernald et al., 1998). While previous authors have denoted the distracter-first trials as "incorrect" in paradigms where visual stimuli had been perceived prior to the auditory onset, it is unlikely that the first fixation is related to processing of the auditory material in this particular case since the direction of the first look appears to be due to chance, that is, around 50% of trials fall in either category. We therefore include the direction of the first look as a fixed factor in our analyses.

Data Preprocessing

Data were preprocessed using custom Matlab software to detect fixations, saccades, and blinks. Only trials where the word was indicated as "understands" on the Oxford CDI were included in the set (this excluded 26% from 18-month-olds and 11% of trials from 24-month-olds). Trials were excluded if the total looking time was lower than 2 SD below the mean (cut-off 748 ms, 4.7% of trials in 18-month-olds, 2.6% of trials in 24-month-olds) or if the latency to the first fixation was smaller than 250 ms (a relatively conservative latency in the sense that it excludes as few trials as possible; cf. Swingley et al., 1999). The rationale for this is that saccades occurring earlier than this cannot be based on the visual stimuli (excluded 10% of trials from 18-month-olds and 5% of trials from 24-month-olds). Trials were also excluded if the latency was longer than 2 SD above the mean latency (i.e., trials in which the child likely did not attend to the experiment at the beginning of the trial and may well have missed the auditory stimulus as well as not looking at the screen; 1% of trials from 18-month-olds and 2% of trials from 24-month-olds). Trials with extremely short or long duration of first fixation were also excluded (±2 SD around the mean, 0.2% of trials from 18-month-olds and 0.4% of trials from 24-month-olds).

Direction of First Look

The first fixation was directed at the familiar item in 48.4% of all trials for 18-month-olds and in 49.4% of trials for 24-month-olds. This was not statistically different from chance in either age group (18-month-olds: $p > .43$, 24-month-olds: $p > .71$, binomial tests). It therefore appears that the direction of the first look is overall not driven by the auditory or visual input. However, as we shall see below, the direction of the first look is an important factor in looking time across the trial and therefore included in all analyses.

Overall Proportion of Looking at Familiar Item

Corresponding to the most established metric in preferential looking, we first calculated the overall proportion of looking directed at the familiar item for each trial by summing up eye-tracking samples (8.33 ms each) during which the fixation location was recorded as directed at the familiar item and dividing by the amount of total looking (familiar item plus novel item) recorded on the relevant trial. Figure 3 shows plots for the proportion of looking directed at the familiar item across the whole trial for all conditions and age groups. In order to determine the best-fitting model, we began with a base model and added relevant effects in a stepwise fashion with the aim of using pairwise model comparisons to evaluate which effects contributed to improving the model fit. Models were fitted to arcsine-transformed data to avoid using data bounded by 0 and 1.

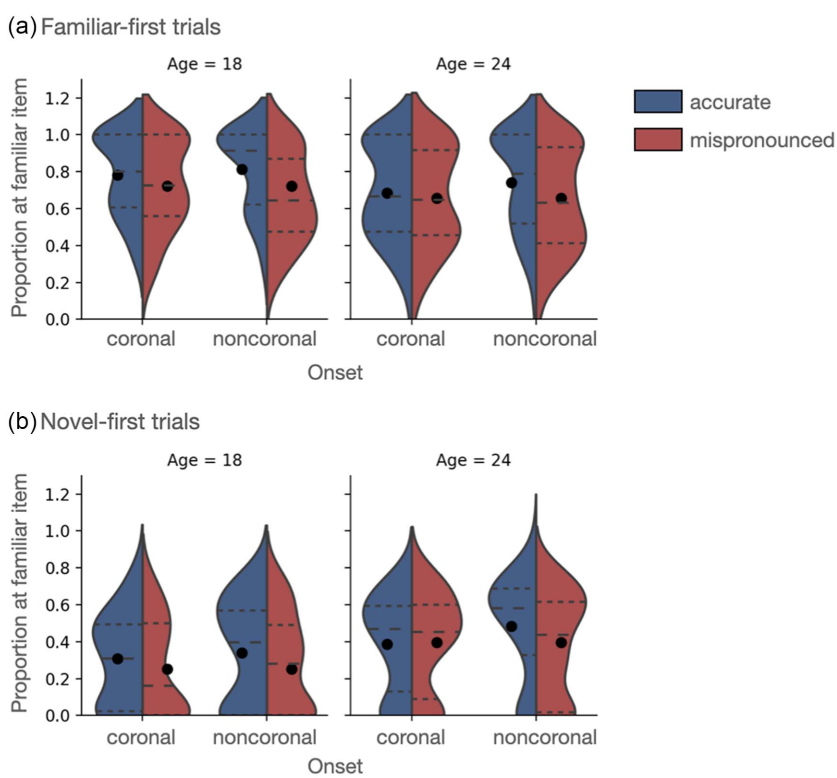
We first constructed a linear mixed-effects model with only random effects of subjects and items (familiar item) on the intercepts. We then added fixed effects Direction of first look (familiar, novel), Condition (accurate, mispronounced), Onset (coronal, noncoronal), and Age (18, 24) as well as interactions. All models were fitted using the lme4 package in R (Bates et al., 2015).

Model comparisons (see Table A1) showed that adding the Direction of first look improved the model fit, $\chi^2(1) = 361.8$, $p < .0001$, and so did adding the fixed effect of Condition, $\chi^2(1) = 6.04$, $p = .014$. Adding an interaction of Direction and Condition did not improve the fit and nor did adding a main effect of Onset or two- or three-way interactions of Direction, Condition, and Onset. Adding the main effect of Age led to a trend for an improved fit, $\chi^2(1) = 3.27$, $p = .071$. Of the two-way interactions, only the addition of an interaction of Direction of First Look × Age improved the fit, $\chi^2(2) = 22.24$, $p < .0001$. None of the three-way interactions improved the fit. The best-fitting model is therefore the one with the main effects of Direction of first look, Condition, and Age and an interaction of Direction of First Look × Age. The model is summarized in Table 2. The best-fitting model shows the main effects of Direction of first look and Condition and an interaction of Direction of First Look × Age (but no main effect of Age).

Discussion of Looking Proportions

The clear difference between familiar-first and novel-first trials (main effect of Direction of first look) demonstrates that as a group infants clearly know the words and respond to them—they do not treat familiar and novel images the same way and spend considerably more time on the familiar item after having heard either the correct or mispronounced version of the target word. The main effect of Condition reflects the fact that there is an overall mispronunciation effect: infants looked longer at the familiar item when they had heard an accurate pronunciation. The Direction of First Look × Age interaction reflects most likely a change in processing speed. Eighteen-month-olds take longer to disengage from the first item, which means that differences between trials on which the familiar item was encountered first versus those on which the novel item was encountered first are exaggerated at 18 months compared to 24 months. However, adding Onset main effects and interactions to the model did not improve the fit, suggesting that there is no systematic asymmetry between coronals and noncoronals as far as overall preferential looking is concerned.

Figure 3
Proportion of Looking Directed at the Familiar Item



Note. Violin plots of the proportion of looking directed at the familiar item for (a) familiar-first trials and (b) novel-first trials. Dashed lines indicate median and quartiles; black dots show the mean. See the online article for the color version of this figure.

Table 2
Model Summary for Best-Fitting Model of Overall Proportion of Looking at the Familiar Item

Model	Estimate	*SE*	*df*	*t*	*p*
Base	7.35E-01	9.35E − 02	5.62E + 01	7.862	<.0001***
DirectionOFL (Direction of first look)	6.27E − 01	8.24E − 02	1.01E + 03	7.606	<.0001***
Condition	−9.27E − 02	3.59E − 02	1.66E + 02	−2.583	.011*
Age	6.61E − 03	4.07E − 03	4.52E + 01	1.623	.1116
DirectionOFL × Age	−1.74E − 02	3.76E − 03	1.01E + 03	−4.629	<.0001***

Note. *SE* = standard error.
* indicates significance at the .05 level. *** at the .0005 level.

Growth Curve Modeling

In order to examine the time course of looking, we used a growth curve approach (Mirman, 2014). In this study, the auditory label was presented before the visual onset, unlike many preferential looking studies, in which the label is presented halfway through the visual presentation. Infants therefore did not look at one of the items while hearing the label. However, as the above analysis demonstrates, the likelihood of landing the first fixation on either the novel or the familiar image is about 50%. As we have seen above, and further visual inspection confirmed, looking patterns across the trial unfolded in very different ways depending on which item this first fixation landed on. In order to analyze the time course of looking across the trial, we therefore divided the set into familiar-first trials (FF) and novel-first (NF) trials. Figures 4 and 5 show the proportion of looking at the item first fixated over time. This division allowed us to compare changes in looking over time with all trials starting at the same point: At the beginning of the trial, the proportion of looks directed at the first-fixated image is trivially 1. Since looking proportions began to decrease around 1,000 ms into the visual presentation,[2] we selected the interval from 950 ms until 2000 ms for the growth curve analysis (samples were aggregated across four consecutive eye-tracking samples of 8.33 ms, i.e., 33.32 ms).

Since patterns for familiar-first (FF) and novel-first (NF) trials show different shapes, they needed to be fitted with separate models.[3]

We fitted logistic mixed-effects models to the data using the lme4 package in R (Bates et al., 2015). Unlike linear linking functions, which have recently been criticized in the context of growth curve analysis for visual world paradigms (Huang & Snedeker, 2020), this takes into account that the response is binary in the sense that the participant is at any point in time either looking at the target or not. After visual inspection, we fitted third-order orthogonal polynomials to the time course data (for the 950–2,000 ms window). For both models (FF and NF), the base model specified only time terms and random effects of Participant and Item on the intercepts. We then added fixed effects of Condition (correct, mispronounced, novel), Onset (coronal, noncoronal), and Age (18, 24) in a stepwise procedure, using model comparisons to evaluate their impact on the model fit. In the following sections, we only list those effects whose addition improved the model fit for the sake of clarity. The full results are provided in Tables A2–A5.

Familiar-First Model

Figure 4 shows data and model predictions for 18- and 24-month-olds, for the best familiar-first model.

The model fit was improved by the addition of a fixed effect of Condition on the intercept, $\chi^2(1) = 779.34$, $p < .0001$; an effect of Onset on the linear term, $\chi^2(1) = 11.57$, $p = .015$; and an effect of Age on the linear, $\chi^2(1) = 138.22$, $p < .0001$, quadratic, $\chi^2(1) = 10.16$, $p = .001$, and cubic time terms, $\chi^2(1) = 6.91$, $p = .009$. The addition of a two-way interaction of Condition × Onset on the intercept, $\chi^2(1) = 210.51$, $p < .0001$; the linear, $\chi^2(1) = 9.35$, $p = .002$; quadratic, $\chi^2(1) = 8.78$, $p = .003$; and cubic, $\chi^2(1) = 8.78$, $p = .003$, also improved the model.

Importantly, adding the three-way interaction of Condition × Onset × Age on intercept, $\chi^2(3) = 173.59$, $p < .0001$, and time terms, linear: $\chi^2(3) = 199.53$, $p < .0001$, quadratic: $\chi^2(3) = 8.02$, $p = .046$, cubic: $\chi^2(3) = 15.31$, $p = .002$, also led to significant improvements.

The complete results for the stepwise model comparisons can be found in Table A2, and the final best-fitting model is summarized in Table A3.

While the model comparisons show that looking patterns are different across combinations of age, pronunciation, and onset type, they do not per se tell us for which words there was a clear mispronunciation effect in the two age groups. We therefore used the *multcomp* package (Hothorn et al., 2008) in order to conduct pairwise post hoc comparisons. These confirmed that for 18-month-olds there was a clear mispronunciation effect both for coronal ($z = 10.14$, $p < .001$) and noncoronal ($z = 10.96$, $p < .001$) items. By contrast, 24-month-olds only showed a significant mispronunciation effect for noncoronals ($z = 16.26$, $p < .001$). For coronal items, the difference between accurate and mispronounced trials was not significant ($z = .185$, $p = 1$).

Novel-First Model

Figure 5 shows data and model predictions for 18- and 24-month-olds, for the best novel-first model, that is, covering those trials where the first fixation was landed on the novel item.

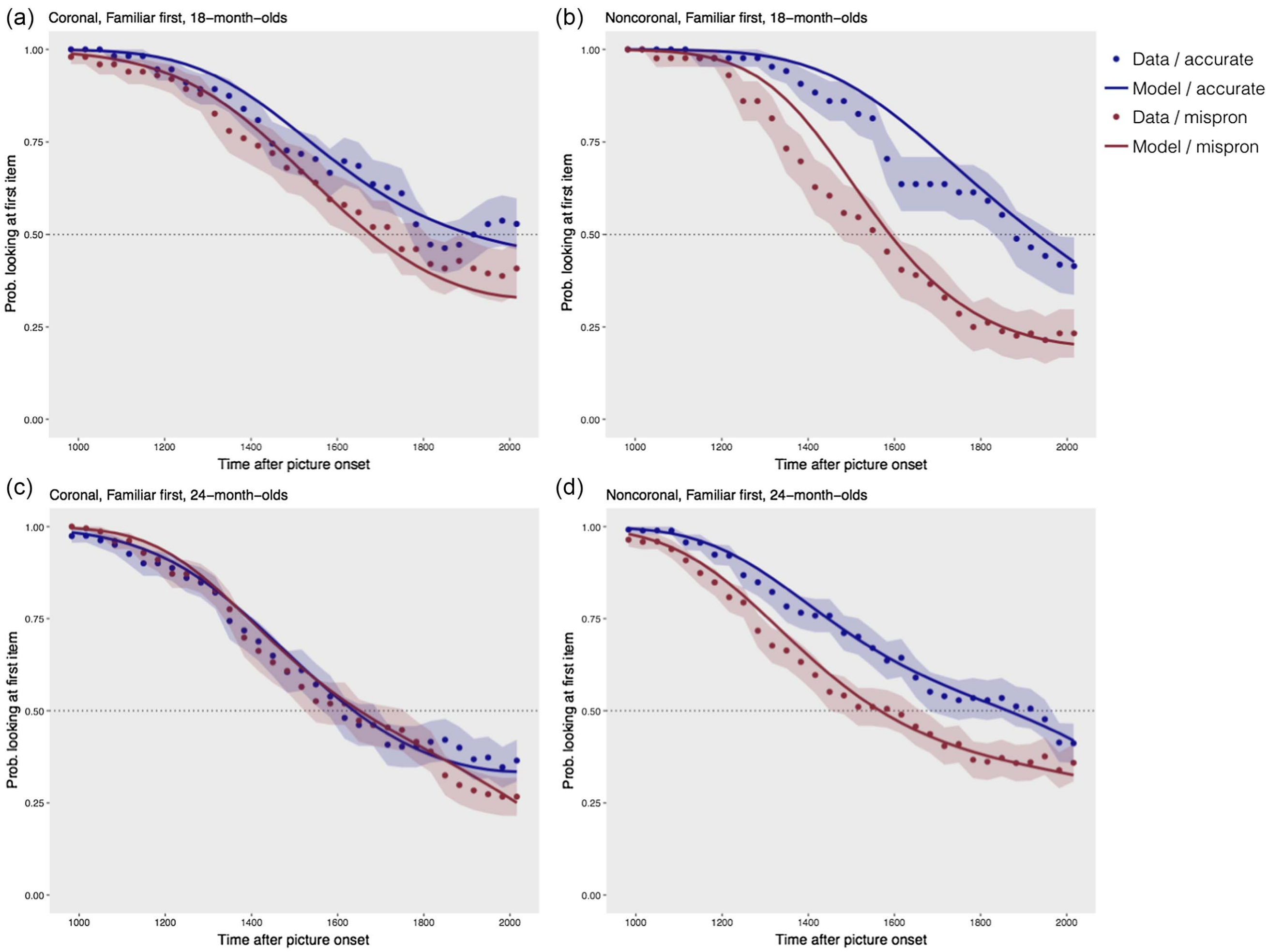
The base model was improved by the addition of a fixed effect of Condition (accurate, mispronounced) on the intercept, $\chi^2(1) = 529.51$, $p < .0001$, and on the quadratic, $\chi^2(1) = 15.33$, $p < .0001$,

[2] The interval between 0 and 1,000 ms after visual stimulus onset includes the period where saccades are landed. As the likelihood of fixating the first item is calculated by dividing the number of trials with looking is directed at that item by the number of trials on which looking is directed at this or the other item (but not trials without looking at this time point), the proportion is 1 until there is at least one trial on which the infant has moved to the other image.

[3] Fitting models to the entire data set (i.e., containing FF and NF trials) led to convergence issues and did not yield good enough model fits.

Figure 4

Familiar-First Model: Data and Predictions for Model Fitted to Trials Where the First Fixation Fell on the Familiar Item



Note. Dotted lines show mean proportions directed at the familiar item; shaded areas show standard errors of the mean. Solid lines show model prediction. (a) Target items with coronal onset (e.g., dog), 18-month-olds. (b) Target items with noncoronal onset (e.g., bear), 18-month-olds. (c) Target items with coronal onset, 24-month-olds. (d) Target items with noncoronal onset, 24-month-olds. See the online article for the color version of this figure.

time term, by the addition of a fixed effect of Onset (coronal, noncoronal) on the linear, $\chi^2(1) = 7.3$, $p = .007$, and cubic time terms, $\chi^2(1) = 18.58$, $p < .0001$, the addition of a fixed effect of Age on the intercept, $\chi^2(1) = 8.99$, $p = .0027$, the linear, $\chi^2(1) = 147.4$, $p < .0001$, and quadratic time terms, $\chi^2(1) = 16.78$, $p < .0001$.

The addition of a Condition × Onset interaction on the intercept, $\chi^2(1) = 235.25$, $p < .0001$, linear and quadratic time terms, linear: $\chi^2(1) = 47.96$, $p < .0001$, quadratic: $\chi^2(1)=36.39$, $p < .0001$, further improved the fit. Crucially, adding the three-way interaction of Condition × Onset × Age on intercept, $\chi^2(3) = 35.96$, $p < .0001$, and time terms, linear: $\chi^2(3)=8.78$, $p = .03$, quadratic: $\chi^2(3) = 35.02$, $p < .0001$, cubic: $\chi^2(3) = 28.69$, $p < .0001$, improved the model further. The complete results for model comparisons as well as the final best-fitting model summary are found in Tables A4 and A5.

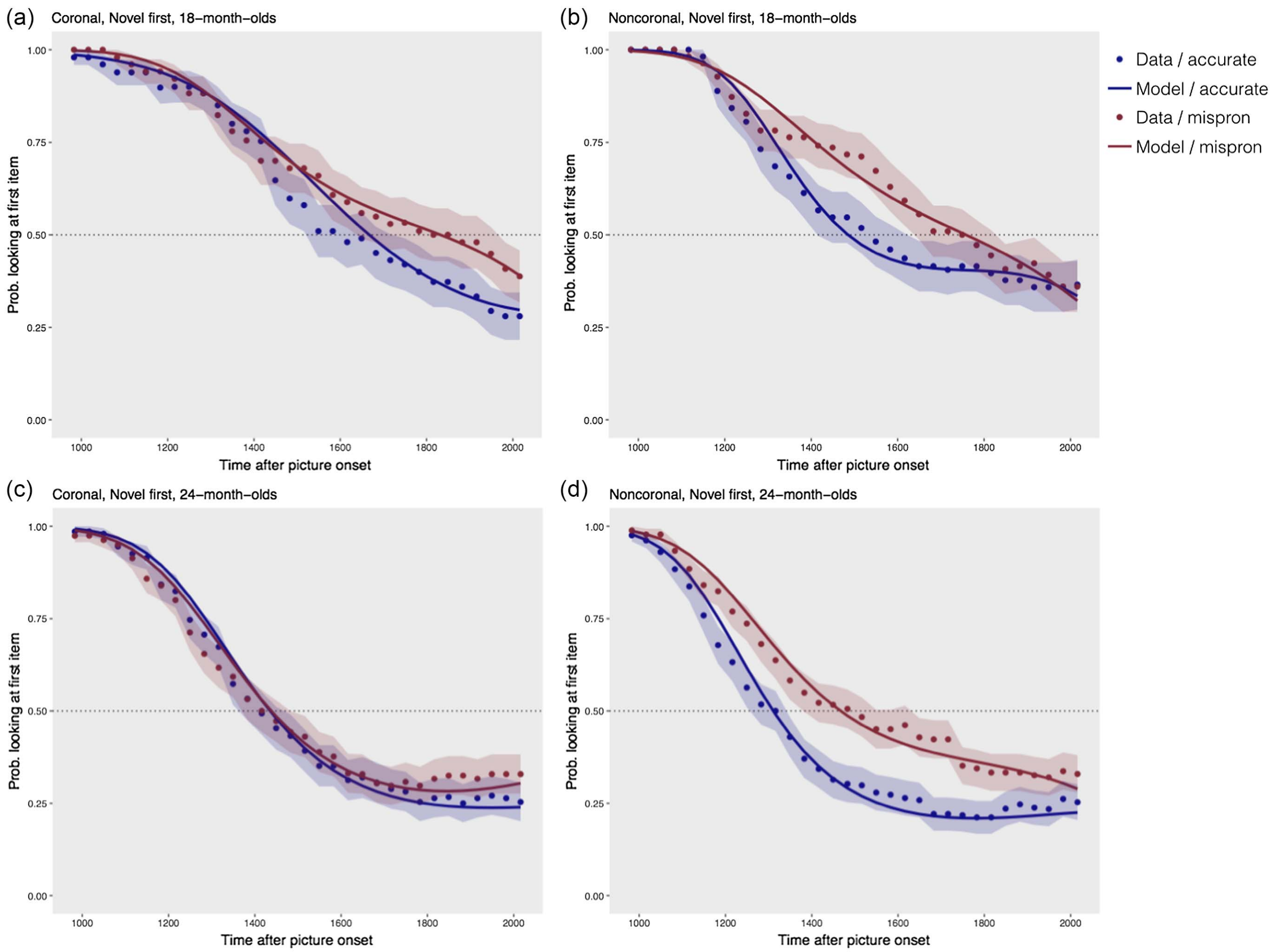
Pairwise comparisons using the *multcomp* package showed that for 18-month-olds the curves for coronals were different (accurate mispronounced $z = -6.17$, $p < .001$), as were those for noncoronals ($z = -4.35$, $p < .001$). For 24-month-olds, the contrast for coronals was not significant ($z = -.05$, $p = 1$), but for noncoronals, there was a clear difference between accurate and mispronounced items ($z = -20.49$, $p < .001$).

Discussion of Growth Curve Models

Here, we presented an intermodal preferential looking task with 18- and 24-month-old infants to investigate mispronunciation sensitivity for words beginning with coronal and noncoronal sounds; that is, [t d n] versus [p b m]. Whereas word recognition models such as TRACE, and many previous studies testing infants' mispronunciation sensitivity, predict that the representations of both types of sounds should be detailed early on in the lexicon (and remain so), the FUL model predicts that coronal sounds are underspecified in the lexicon. According to this hypothesis, mispronunciation sensitivity should be diminished for words beginning with such sounds.

Figure 5

Novel-First Model: Data and Predictions



Note. Dotted lines show mean proportion of looking at the novel item, shaded areas indicate standard errors of the mean, and solid lines show model predictions. (a) Target items with coronal onset (e.g., dog), 18-month-olds. (b) Target items with noncoronal onset (e.g., bear), 18-month-olds. (c) Target items with coronal onset, 24-month-olds. (d) Target items with noncoronal onset, 24-month-olds. See the online article for the color version of this figure.

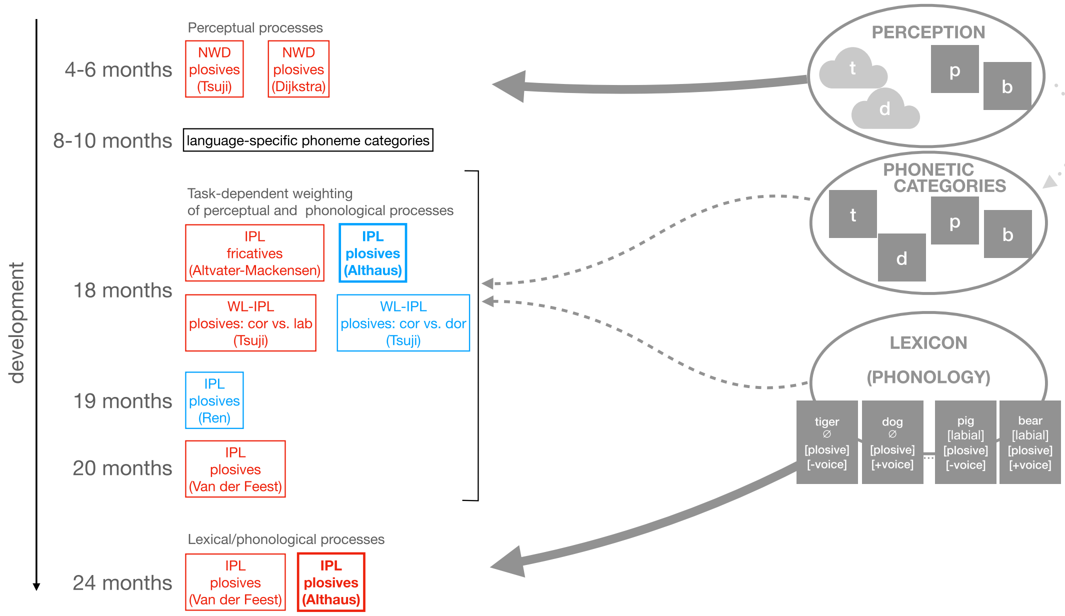
Although our initial tests of preferential looking averaged across the whole trial did not show differences between the two types of words, a detailed growth curve analysis of children's looking patterns over time revealed asymmetries between coronal and non-coronal-onset words at 24, but not 18, months.

Although we fitted two separate models to accommodate the differing curve shapes of looking patterns in familiar-first versus novel-first trials, the results were similar for both trial types. The stepwise model comparison for each model demonstrated that all three fixed effects, Age, Condition, and Onset, significantly impacted on the shapes of the looking pattern. Post hoc tests confirmed that at 18 months children show sensitivity to both types of mispronunciation. Here, looking patterns differed for mispronounced trials compared to accurately pronounced trials regardless of whether the target word had a coronal or a non-coronal-onset sound. At 24 months, by contrast, the pairwise post hoc tests confirmed a clear asymmetry. While children in this age group continued to show a clear mispronunciation effect for noncoronals, for example, *[dɛː] instead of [bɛː] (*bear*), there was no evidence for mispronunciation sensitivity for coronal-onset words. Looking responses to *[bʌk] (**buck* instead of *duck*) were similar to those for accurate [dʌk]. Hearing a mispronunciation of a coronal apparently activates the lexical entry (here: *duck*) just as well as hearing the accurately pronounced item. By contrast, the mispronunciation effect for noncoronals shows that pronouncing a noncoronal as a coronal sound (e.g., *[dɛː] for *bear*) does not activate the lexical entry, or at least not as well as the accurately pronounced stimulus [bɛː]. Where the children first landed on the noncoronal familiar items, 24-month-olds who had heard a mispronounced version of the target word moved away from this stimulus more rapidly than those who had heard the accurate version, shifting their eyes to the novel item instead, Figure 4c versus 4d. This is evidence that what infants heard is, to them, not a match for the item they are looking at, implying that *[dɛː] is perceived as a different word.

In particular, the effects found at 24 months are consistent with the predictions made by coronal underspecification and the FUL

Figure 6

A Schematic Timeline of the Relationship Between Emerging Coronal Underspecification and Mispronunciation Asymmetry



Note. Red rectangles represent studies demonstrating asymmetries; blue rectangles represent studies that found no asymmetries. Studies from the present article in bold. NWD = nonword discrimination; IPL = intermodal preferential looking; WL-IPL = word learning/intermodal preferential looking. See the online article for the color version of this figure.

model: Since the onset consonant for "duck" is not specified for a place feature according to this model, *[bʌk] contains all required features ([PLOSIVE] and [+VOICE]) to activate the lexical entry *duck*. By contrast, the mispronunciation *[dɛː] does not activate *bear*, because the noncoronal place feature [LABIAL] that is required is not present in the input.

Although the shape of the curves at 18 months (and the seemingly smaller gap between the curves for accurate and mispronounced trials) may hint at the first signs of an emerging asymmetry between coronals and noncoronals, statistically there is a mispronunciation effect for both groups of words, with no evidence that this is larger for one type or the other. This is interesting because it implies that the asymmetry is not present from the beginning of lexical development but emerges over time.

General Discussion

Coronal asymmetries have been reported across different age groups and languages (Altvater-Mackensen et al., 2014; Dijkstra & Fikkert, 2011; Friedrich et al., 2006, 2008; Roberts et al., 2013; Tsuji et al., 2015; Van der Feest & Fikkert, 2015; Wheeldon & Waksler, 2004). The present findings are mainly in line with these and shed additional light on the time course of development. In our study, fine-grained looking patterns across time revealed that infants at 18 months are sensitive to mispronunciations of both noncoronal- and coronal-onset words, whereas 24-month-olds exhibited the asymmetry predicted by the FUL model, that is, sensitivity to mispronunciation of noncoronal but not of coronal sounds. What is the explanation for this developmental pattern? Here, we present a model of lexical development that is consistent with these results as well as earlier results.

Our model proposes that (a) the processes involved in speech processing change with development and younger toddlers rely more on matching acoustic patterns, whereas older toddlers rely on the activation of lexical entries, and (b) that lexical entries are constructed to reflect structured variability in the input, a process that requires tracking statistical patterns that may only become detectable with increased experience. The concept of coronal underspecification is not incompatible with accurate auditory *discrimination* of correct and mispronounced forms (adults can *hear* the difference between forms like [dʌk] and [bʌk], after all, even though in ERP and reaction time studies they reliably show evidence for underspecification). Instead, coronal underspecification is concerned with the question of whether a lexical entry is activated to the same degree by the accurate and mispronounced items. Infants' ability to interpret acoustic input and activate a corresponding lexical entry has previously been shown to change during the first year of life. For instance, between 8 and 10 months, responses to words uttered by a caregiver show higher recognition than the same words uttered by a stranger (Bergelson & Swingley, 2018; Parise & Csibra, 2012). In the same way, 18-month-olds' ability to activate lexical entries may depend more on an acoustic exact match for coronals than that of 24-month-olds, even if their *grammatical* representation does not specify a [CORONAL] feature. This view is compatible both with the findings of asymmetries in studies involving familiarization in the first year of life (Dijkstra & Fikkert, 2011; Tsuji et al., 2015), studies not finding asymmetries in the middle of the second year (Ren et al., 2019, with 19-month-olds; the present results with 18-month-olds), and our present work with 24-month-olds, in which asymmetries are found. We illustrate this model in Figure 6.

The assumption is that perceptual processes are distinct from phonological processes and that lexical entries are established with the first words being learned. In early stages of speech processing, children therefore only have perceptual processes available to discriminate speech sounds or words containing them. At this stage, acoustic and motor asymmetries are the only mechanisms that can cause asymmetrical responses to mispronunciations. This is what we see in discrimination studies with nonwords (Dijkstra & Fikkert, 2011; Tsuji et al., 2015) at 4 and 6 months, and this is consistent with the idea that coronals are acoustically more variable in speech, regardless of their phonological distribution within words or phrases. In addition, the tongue is in a neutral position. This may be relevant in the sense that for noncoronals infants may activate additional visual speech or motor features during discrimination experiments, but may not do so for coronals.

We know, however, that despite these early asymmetries infants are eventually capable of discriminating between minimal pairs with a coronal–noncoronal contrast (even within the short time frame allowed in a single lab session). For instance, Stager and Werker's (1997) auditory control experiment with 14-month-olds (bih vs. dih) presents evidence for this. So by 18–20 months, we know that infants can discriminate coronal versus noncoronal sounds perceptually, but their lexical entries may still be immature. At this age, we see seemingly contradictory findings (asymmetries in Altvater-Mackensen et al., 2014; Tsuji et al., 2016; Van der Feest & Fikkert, 2015; no asymmetries in the present study, Ren et al., 2019; Tsuji et al., 2016). However, a closer look shows that there is a systematicity here if we consider both task demands and the type of contrast that is being tested. Eighteen-month-olds show sensitivity for contrasts that are perceptually easier to discriminate, such as dorsal versus coronal consonants in Tsuji et al.'s (2016) word learning study or for more difficult consonant contrasts in less demanding tasks such as intermodal preferential looking with familiar words (our study). The same age group does NOT show sensitivity for harder-to-discriminate contrasts (fricatives; Altvater-Mackensen et al., 2014) or in harder tasks (novel word learning of coronal/labial contrasts; Tsuji et al., 2016). Ren et al.'s work with 19-month-olds is compatible with this, presenting results from a low-demand task with familiar items (which is in particular likely to be made less sensitive by the presence of the salience phase; see above), and not showing an asymmetry. We therefore propose that 18 to 19 months represents an intermediate stage at which both the lexicon and the word learning process are immature and based on limited evidence for what is an acceptable word form, and word learning therefore relies on a mixture of perceptual and phonological (lexical) processes, leading to a highly task-dependent behavioral pattern. We argue that at this stage children may not yet have sufficient segmentation, grammatical, and lexical abilities in order to detect alternations like [reim] as an acceptable version of *rain*. Only once longer strings of words are fully analyzed can the learning system begin to represent regularities such as coronal assimilations. There is evidence that such changes occur between 18 and 24 months. A study by (Plunkett, 2006) tested 18- and 24-month-olds' ability to demonstrate word recognition in an intermodal preferential looking task in which target words were presented in three conditions: (a) presented in isolation, with target words recorded as isolated words; (b) presented in isolation, but with words cut from sentences ("coarticulated target words"); and (c) target words embedded in fluent speech. The results support the idea that segmenting words from fluent speech is a challenge that may cause 18-month-olds to fail, whereas 24-month-olds can manage. In this study, 18-month-olds' target preference was decreased for words in a sentence context compared to forms recorded and presented in isolation form. Even for words presented in an isolated form but with targets cut from a sentence recording (i.e., containing coarticulation), 18-month-olds did not show significant target recognition.

The regularity underlying alternations such as the assimilation of [n] to [m], [d] to [b], and [t] to [p] only become accessible once speech segmentation has been mastered. Perhaps, the gradually emerging distribution of these alternations tips the system toward using a phonological representation over a perceptual one, where under-specification allows for such variability. Where the [CORONAL] feature is no longer a part of the acoustic input, a sequence of sounds such as [faɪm] for *find* in "Can you find my cup?" can then still activate the lexical entry for *find*. As a consequence, mispronunciations are tolerated, even in the onset positions we tested in the present work, where assimilations are not found in the actual input. At 18 months, by contrast, infants still utilize a more direct route between early auditory representations and semantic information and as a result exhibit mispronunciation sensitivity that contrasts with that of older children and adults.

By 24 months, there is converging evidence for underspecification (our study and Van der Feest & Fikkert, 2015). Infants may have acquired a sufficient vocabulary and become sufficiently skilled at speech segmentation for the alternations of coronals in noncoronal contexts to register as a pattern. Now, forms like [reim] can be picked up as variants of rain, and accordingly, the lexical entry is adjusted in such a way that a coronal sound is no longer required to activate this lexical entry. The most straightforward way to do this is simply to accept variability for the phonological place feature—and this equates to underspecifying the lexical entry. Simultaneously, or perhaps precisely because the lexicon is mature enough, the system becomes less reliant on perception, and phonological matching processes govern looking behavior. Naturally, these are emerging processes that do not "flip" within a short span of time. Van der Feest et al.'s results from 20-month-olds suggest that such behavior is possible earlier than at 24 months.

Considering previous studies across the first 24 months, then, our results are entirely consistent with other findings assuming the model described here. Perhaps most importantly, our findings contradict Ren et al.'s claim that there is no evidence for asymmetries in the developing lexicon. Their testing age of 19 months may have been too early to pick up on asymmetries. There are, however, also a few design aspects that may have allowed us to obtain a more fine-grained pattern of results than is often the case in intermodal preferential looking studies. As the discrepancy between our tests of preferential looking averaged across the trial and the growth curve analysis demonstrates, the phenomenon is subtle. Looking patterns clearly need to be analyzed at a fine-grained scale. Here, we used a combination of repeated measures (every child was presented with both an accurate and a mispronounced version of the same word) and linear mixed-effects modeling to capture the effects of onset and pronunciation, which allows the model to account for variability between target words, for example. Another factor we deem to be important is the division into trials on which the first look was directed at the familiar item and those on which the first look was directed at the novel item. As our results show, the shapes of the curves are quite different, and this is not actually surprising, especially, in the context of familiar versus novel items (earlier studies using intermodal preferential looking also took into consideration that switching from a distracter to a named target is different from remaining on a named target after already having spent some time on it, e.g., Fernald et al., 1998). Not considering the effect of the direction of the first look may result in any effects being obscured. The variability that is found in a data set containing both types of trials is so large that discrepancies induced by the onset manipulation may not emerge as statistically relevant. We believe this is a crucial aspect of our analysis.

One of the most important design elements, perhaps, is the presentation of auditory targets before the visual stimuli are being shown. That infants by 18 months "implicitly name" visual targets, that is, generate corresponding labels, has been demonstrated previously (Mani & Plunkett, 2010, 2011). In a study investigating mispronunciation sensitivity with a paradigm that displays images before presenting the auditory stimuli, this could be disastrous: Upon presentation of a "duck" or "bear," for instance, infants may generate the labels /dʌk/ or /bɛ:/, respectively. In particular, this means that the lexical entries corresponding to these words may *already be active* at the time the auditory stimuli are heard. It is not clear how the infant would be expected to behave in this case: None of our models make specific predictions about matching incoming auditory material to an already activated mental lexical entry. It could be that a clash is somehow perceived for mispronunciations. But it could also be the case that both accurate and mispronounced signals are simply "absorbed" into the already existing activation pattern, that is, the activation pattern is already as active as it ever will be, and therefore the familiar item (in the present study) is a perfectly fine visual referent for either. Were that to happen, the study could not detect mispronunciation sensitivity simply because the study does not test the ability of mispronounced words to activate the corresponding lexical entry.

Previous studies, in particular Ren et al. (2019), used paradigms in which participants had time to generate a label for visual stimuli before the accurate or mispronounced label was presented. Ren et al. (2019) did so explicitly in order to assess prior preferences for the visual stimuli. It therefore cannot be excluded that the 19-month-olds in their study generated labels during this pre-exposure, and this would have obscured any asymmetry between accurate and mispronounced items.

In summary, we have presented a study reporting asymmetries in mispronunciation sensitivities for coronal versus noncoronal items at 24 months but not at 18 months, where infants are sensitive to mispronunciation of both types of onset sounds. We showed that highly sensitive data acquisition methods and analysis techniques can tap into even subtle differences in toddlers' lexical representation that previous approaches missed. We believe the observed emerging asymmetry reflects changes in the mental lexicon. It appears that a lexical entry such as *bear* at 24 months clearly specifies the place feature, which means that during processing, if the place feature is not present in the input, the auditory signal is treated as not matching. By contrast, a lexical entry such as *duck* does not specify the place feature and therefore the incoming acoustic signal can match even if it contains a noncoronal. At 18 months, this asymmetry is not yet clearly measurable. At this stage in development, word recognition appears to be driven by phonetic representations, that is, tied to specific acoustic properties, rather than phonological ones, which are tied to *phonological features.* We believe that the changes between 18 and 24 months which we observe here are driven by experience with the input language (cf. Lahiri & Reetz, 2010). Increasing experience with words in a syntactic context, and therefore assimilated occurrences, causes a *phonological* representation to emerge that does not specify the place of articulation for coronal items. For noncoronals, by contrast, the representation always contains the place feature as there is no variability in the input signal to drive underspecification. The gradual emergence of coronal underspecification is evidence of a phonological learning process that is closely tuned to variability in the input and shows that phonological feature representations are adaptable to achieve an efficient mental lexicon.

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(*Appendix follows*)

Appendix

Detailed Model Results

Table A1
Stepwise Model Comparisons for Overall Proportion of Looking at the Familiar Item

Model	npar	AIC	BIC	logLik	Deviance	χ^2	*df*	*p*
Base	4	1221.72	1241.5	−606.86	1213.72			
DirectionOFL (Direction of first look)	5	861.92	886.66	−425.96	851.92	361.7953	1	<.0001***
Condition	6	857.88	887.56	−422.94	845.88	6.0431	1	.01396*
DirectionOFL × Condition	7	859.48	894.11	−422.74	845.48	0.3987	1	.52777
Onset	8	861.41	900.98	−422.7	845.41	0.0739	1	.78573
Condition × Onset	9	862.27	906.79	−422.13	844.27	1.1358	1	.28653
DirectionOFL × Onset	10	864.26	913.73	−422.13	844.26	0.0067	1	.93466
DirectionOFL × Condition × Onset	11	866.09	920.51	−422.04	844.09	0.1742	1	.67644
Age	12	864.82	924.19	−420.41	840.82	3.2673	1	.07067(*)
Condition × Age	13	866.28	930.59	−420.14	840.28	0.5464	1	.45978
Onset × Age	14	866.53	935.79	−419.26	838.53	1.7478	1	.18615
DirectionOFL × Age	15	848.04	922.24	−409.02	818.04	20.4884	1	<.0001***
Condition × Age × Onset	16	849.23	928.38	−408.62	817.23	0.8083	1	.36863
Condition × Age × DirectionOFL	17	850.04	934.14	−408.02	816.04	1.1877	1	.2758
Condition × Age × Onset × DirectionOFL	19	852.4	946.39	−407.2	814.4	1.647	2	.43888

Note. npar = number of parameters; AIC = Akaike information criterion; BIC = Bayesian information criterion.
(*) $p < .1$. * $p < .05$. *** $p < .001$.

Table A2
Stepwise Model Comparisons for Familiar-First Model

Model	npar	AIC	BIC	loglik	Deviance	χ^2	*df*	*p*
Base	6	54,238	54,284	−27,113	54,226			
Condition (intercept)	7	53,461	53,515	−26,724	53,447	779.3351	1	<.0001***
Condition linear	8	53,460	53,521	−26,722	53,444	3.2875	1	.07(*)
Condition quadratic	9	53,461	53,530	−26,722	53,443	0.3842	1	.535
Condition cubic	10	53,463	53,540	−26,722	53,443	0.0177	1	.894
Onset (intercept)	11	53,465	53,550	−26,722	53,443	0.2351	1	.628
Onset linear	12	53,461	53,553	−26,719	53,437	5.8743	1	.015*
Onset quadratic	13	53,462	53,562	−26,718	53,436	1.2502	1	.264
Onset cubic	14	53,464	53,571	−26,718	53,436	0.0728	1	.787
Condition × Onset (Intercept)	15	53,255	53,371	−26,613	53,225	210.5137	1	<.0001***
Condition × Onset Linear	16	53,248	53,371	−26,608	53,216	9.3467	1	.002**
Condition × Onset Quadratic	17	53,241	53,372	−26,604	53,207	8.7793	1	.003**
Condition × Onset Cubic	18	53,239	53,377	−26,602	53,203	4.2534	1	.039*
Age (intercept)	19	53,239	53,385	−26,600	53,201	2.2652	1	.132
Age linear	20	53,103	53,256	−26,531	53,063	138.2158	1	<.0001***
Age quadratic	21	53,094	53,256	−26,526	53,052	10.1586	1	.001**
Age cubic	22	53,090	53,258	−26,523	53,046	6.9129	1	.009**
Condition × Onset × Age (Intercept)	25	52,922	53,114	−26,436	52,872	173.5892	3	<.0001***
Condition × Onset × Age Linear	28	52,728	52,943	−26,336	52,672	199.53	3	<.0001***
Condition × Onset × Age Quadratic	31	52,726	52,964	−26,332	52,664	8.0244	3	.046*
Condition × Onset × Age Cubic	34	52,717	52,978	−26,324	52,649	15.3065	3	.002**

Note. npar = number of parameters; AIC = Akaike information criterion; BIC = Bayesian information criterion.
(*) $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

(*Appendix continues*)

Table A3

Parameter Estimates for Best-Fitting Familiar-First Model, With Respect to Base Condition: Correct / Onset: Coronal / Age: 18 Months

Coefficient	Estimate	*SE*	*z*	*p*
Intercept	1.90616	0.35228	5.411	<.0001***
Linear	−10.65904	0.47654	−22.367	<.0001***
Quadratic	3.62096	0.4141	8.744	<.0001***
Cubic	−0.52741	0.29176	−1.808	.071(*)
Condition intercept	−0.78541	0.07795	−10.076	<.0001***
Onset intercept	0.87357	0.42591	2.051	.040*
Age intercept	−0.4267	0.272	−1.569	.117
Condition linear	1.7481	0.55802	3.133	.002**
Condition quadratic	−1.51176	0.49448	−3.057	.002**
Condition cubic	0.67932	0.37301	1.821	.069(*)
Onset linear	−3.77019	1.01944	−3.698	.0002***
Onset quadratic	−0.01023	0.83706	−0.012	.990
Onset cubic	−0.0855	0.51852	−0.165	.869
Age linear	5.45048	0.51277	10.63	<.0001***
Age quadratic	−1.24329	0.45251	−2.748	.006**
Age cubic	−0.27244	0.35775	−0.762	.446
Condition × Onset Intercept	−0.79057	0.15636	−5.056	<.0001***
Condition × Onset Linear	−0.40292	1.15188	−0.35	.726
Condition × Onset Quadratic	1.73641	0.96467	1.8	.072(*)
Condition × Onset Cubic	−0.28074	0.64664	−0.434	.664
Condition (Correct) × Onset (Coronal) × Age (24) Intercept	−0.48521	0.10307	−4.708	<.0001***
Condition (Correct) × Onset (Coronal) × Age (24) Linear	−4.11738	0.73924	−5.57	<.0001***
Condition (Correct) × Onset (Coronal) × Age (24) Quadratic	0.31907	0.65469	0.487	.626
Condition (Correct) × Onset (Coronal) × Age (24) Cubic	0.57956	0.50135	1.156	.248
Condition (Mispronounced) × Onset (Coronal) × Age (24) Intercept	0.28987	0.09361	3.097	.002**
Condition (Mispronounced) × Onset (Coronal) × Age (24) Linear	−6.77531	0.663	−10.219	<.0001***
Condition (Mispronounced) × Onset (Coronal) × Age (24) Quadratic	2.20889	0.59675	3.702	.0002***
Condition (Mispronounced) × Onset (Coronal) × Age (24) Cubic	−1.21309	0.48252	−2.514	.012*
Condition (Correct) × Onset (Noncoronal) × Age (24) Intercept	−0.77931	0.14595	−5.34	<.0001***
Condition (Mispronounced) × Onset (Coronal) × Age (24) Linear	0.37642	1.07929	0.349	.727
Condition (Mispronounced) × Onset (Coronal) × Age (24) Quadratic	0.3789	0.89867	0.422	.673
Condition (Mispronounced) × Onset (Coronal) × Age (24) Cubic	0.16732	0.59395	0.282	.778

Note. *SE* = standard error; npar = number of parameters; AIC = Akaike information criterion; BIC = Bayesian information criterion.
(*) $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

(*Appendix continues*)

Table A4
Stepwise Model Comparisons for Novel-First Model

Model	npar	AIC	BIC	logLik	Deviance	χ^2	*df*	*p*
Base	6	61,441	61,488	−30,715	61,429			
Condition (intercept)	7	60,914	60,968	−30,450	60,900	529.5072	1	<.0001***
Condition linear	8	60,915	60,977	−30,450	60,899	0.3866	1	.534
Condition quadratic	9	60,902	60,972	−30,442	60,884	15.3273	1	<.0001***
Condition cubic	10	60,902	60,980	−30,441	60,882	1.5458	1	.214
Onset (intercept)	11	60,904	60,989	−30,441	60,882	0.2803	1	.597
Onset linear	12	60,899	60,992	−30,437	60,875	7.2973	1	.007**
Onset quadratic	13	60,901	61,001	−30,437	60,875	0.2234	1	.636
Onset cubic	14	60,884	60,992	−30,428	60,856	18.5819	1	<.0001***
Condition × Onset (Intercept)	15	60,651	60,767	−30,310	60,621	235.248	1	<.0001***
Condition × Onset Linear	16	60,605	60,729	−30,286	60,573	47.9569	1	<.0001***
Condition × Onset Quadratic	17	60,570	60,702	−30,268	60,536	36.3885	1	<.0001***
Condition × Onset Cubic	18	60,570	60,710	−30,267	60,534	2.1065	1	.147
Age (intercept)	19	60,563	60,711	−30,263	60,525	8.9916	1	.003**
Age linear	20	60,418	60,573	−30,189	60,378	147.3919	1	<.0001***
Age quadratic	21	60,403	60,566	−30,180	60,361	16.7847	1	<.0001***
Age cubic	22	60,402	60,572	−30,179	60,358	3.5804	1	0.058(*)
Condition × Onset × Age (Intercept)	25	60,372	60,565	−30,161	60,322	35.9649	3	<.0001***
Condition × Onset × Age Linear	28	60,369	60,586	−30,156	60,313	8.775	3	.032*
Condition × Onset × Age Quadratic	31	60,340	60,580	−30,139	60,278	35.0239	3	<.0001***
Condition × Onset × Age Cubic	34	60,317	60,581	−30,124	60,249	28.6948	3	<.0001***

Note. npar = number of parameters; AIC = Akaike information criterion; BIC = Bayesian information criterion.
(*) $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

(*Appendix continues*)

Table A5

Parameter Estimates for Best-Fitting Novel-First Model, With Respect to Base Condition: Correct / Onset: Coronal / Age: 18 Months

Coefficient	Estimate	*SE*	*z*	*p*
Intercept	0.98733	0.33489	2.948	.003**
Linear	−9.08654	0.29075	−31.252	<.0001***
Quadratic	1.82512	0.26408	6.911	<.0001***
Cubic	0.16488	0.2263	0.729	.466
Condition intercept	0.45014	0.07204	6.248	<.0001***
Onset intercept	0.05571	0.39715	0.14	.888
Age intercept	−0.74602	0.25536	−2.921	.003**
Condition linear	−0.83961	0.51778	−1.622	.105
Condition quadratic	2.02029	0.46536	4.341	<.0001***
Condition cubic	−1.5685	0.36025	−4.354	<.0001***
Onset linear	−3.22261	0.52912	−6.09	<.0001***
Onset quadratic	4.7373	0.47564	9.96	<.0001***
Onset cubic	−2.58053	0.36889	−6.995	< .0001***
Age linear	2.0683	0.4333	4.773	<.0001***
Age quadratic	0.31506	0.3941	0.799	.424
Age cubic	0.11527	0.31965	0.361	.718
Condition × Onset Intercept	−0.09497	0.10575	−0.898	.369
Condition × Onset Linear	2.41141	0.76728	3.143	.002**
Condition × Onset Quadratic	−5.33327	0.6913	−7.715	<.0001***
Condition × Onset Cubic	2.65605	0.53147	4.998	<.0001***
Condition (Correct) × Onset (Coronal) × Age (24) Intercept	0.21748	0.08306	2.618	.009**
Condition (Correct) × Onset (Coronal) × Age (24) Linear	−2.58485	0.57297	−4.511	<.0001***
Condition (Correct) × Onset (Coronal) × Age (24) Quadratic	2.19885	0.52353	4.2	<.0001***
Condition (Correct) × Onset (Coronal) × Age (24) Cubic	−0.99152	0.4365	−2.272	.023*
Condition (Mispronounced) × Onset (Coronal) × Age (24) Intercept	−0.23027	0.08936	−2.577	.01*
Condition (Mispronounced) × Onset (Coronal) × Age (24) Linear	−0.56015	0.63972	−0.876	.381
Condition (Mispronounced) × Onset (Coronal) × Age (24) Quadratic	−0.05974	0.58017	−0.103	.918
Condition (Mispronounced) × Onset (Coronal) × Age (24) Cubic	0.7563	0.45582	1.659	.097(*)
Condition (Correct) × Onset (Noncoronal) × Age (24) Intercept	−0.48481	0.08857	−5.474	<.0001***
Condition (Correct) × Onset (Noncoronal) × Age (24) Linear	1.63214	0.63651	2.564	.010*
Condition (Correct) × Onset (Noncoronal) × Age (24) Quadratic	−2.01186	0.58013	−3.468	.0005***
Condition (Correct) × Onset (Noncoronal) × Age (24) Cubic	1.2838	0.46106	2.784	.005**

Note. *SE* = standard error.
(*) $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

Received August 28, 2023
Revision received March 22, 2024
Accepted April 26, 2024 ■