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Key words

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vowel roundedness

Abstract

Previous research has shown that English infants are sensitive to mispronunciations of vowels in familiar words by as early as 15-months of age. These results suggest that not only are infants sensitive to large mispronunciations of the vowels in words, but also sensitive to smaller mispronunciations, involving changes to only one dimension of the vowel. The current study broadens this research by comparing infants' sensitivity to the different types of changes involved in the mispronunciations. These included changes to the backness, height, and roundedness of the vowel. Our results confirm that 18-month-olds are sensitive to small changes to the vowels in familiar words. Our results also indicate a differential sensitivity of vocalic specification, with infants being more sensitive to changes in vowel height and vowel backness than vowel roundedness. Taken together, the results provide clear evidence for specificity of vowels *and* vocalic features such as vowel height and backness in infants' lexical representations.

1 Introduction

Six-month-old infants listen longer to vowels present in their native language than to non-native vowels (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Polka & Werker, 1994). This suggests that infants begin to display some sensitivity to the phonological content of their language around this time. Similar sensitivity to language specific consonants is acquired soon after, by the end of the first year of life (Werker & Tees, 1984). The change towards language-specific phonetic perception precedes the contrastive use of phonological information in encoding words (Werker & Lalonde, 1988; Werker & Tees, 1984). This might suggest that infants' representations of the words they acquire are phonologically well-specified. However, Stager and Werker (1997) suggest that infants may not have complete access to the phonological detail of early lexical representations. Stager and Werker presented 14-month-old infants with

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two novel word-object pairings. The two labels were minimal pairs differing only in the word-initial consonant (*bih* vs. *dih*). Once infants habituated to the word-object pairings, the label for one of the objects was switched with the other. Infants showed no recognition of the mismatch when tested on minimal pairs, although infants were able to recognize a mismatch if the labels shared no sounds (*lif* vs. *neem*), or if tested at an older age (Werker, Fennell, Corcoran, & Stager, 2002). Stager and Werker argue that the complications inherent in word learning may require functional reorganization causing infants to ignore some phonological information.

Another body of research has shown that infants are sensitive to mispronunciations of familiar words as early as 14 months of age — infants look longer at a target object when its label has been correctly pronounced than when the label has been mispronounced by a single consonant at word onset (Ballem & Plunkett, 2005; Swingley & Aslin, 2000, 2002). Swingley and Aslin (2000, 2002) presented infants with pictures of familiar objects side-by-side on a screen. One of the pictures was then named with either a correct or an incorrect pronunciation. Infants were presented with either close (small) or distant (large) mispronunciations of the vowel or consonant of familiar words. The 14-month-olds found correct pronunciations easier to recognize than incorrect pronunciations, although there were no differences between infants responding to the two different kinds of mispronunciations. However, there was a significant bias towards the target image even upon presentation of mispronunciations. Similarly, Ballem and Plunkett (2005) found that 14-month-olds looked longer at a target object when the familiar target label was correctly pronounced but not when it was mispronounced by a single feature change on the word-initial consonant. This suggests that infants' lexical representations are phonologically well specified as early as 14 months of age; at least as far as the word-initial consonants of familiar words are concerned.

Neither Ballem and Plunkett (2005) nor Swingley and Aslin (2002) systematically analyzed the contribution of vowels to lexical access. It has been suggested that vowels may be more crucial to prosodic access and syntactic bootstrapping, while consonants may be more important during lexical access (Nespor, Pena, & Mehler, 2003). Indeed, recent research by Nazzi (2005) found that 20-month-old French infants could learn two words which differed only by a single consonant while failing to learn two words which differed only by a single vowel. This may also suggest that vowels are less crucial to lexical access than consonants.

In order to test whether vowels affect early lexical recognition, Mani and Plunkett (2007) examined 15-, 18- and 24-month-old infants' sensitivity to mispronunciations of vowels in monosyllabic familiar words. Infants were presented with images of two familiar objects side-by-side on a screen. One of the objects was labeled with either a correct pronunciation or a mispronunciation, where mispronunciations altered only the vowels of the words. The results indicated that infants as young as 15 months of age looked longer at a target object when the target label had been correctly pronounced than when the target label had been mispronounced by a single word-medial vowel.

Similar sensitivity to vocalic information is reported by Curtin, Fennell and Escudero (2006) finding that 15-month-olds are able to distinguish between two words differing by a single vowel in a word-learning habituation task. As in the

Stager and Werker study reported above, Curtin, Fennell, and Escudero presented 15-month-olds with two novel word-object pairings. The two labels were minimal pairs differing only in the word-medial vowel (*dit* vs. *deet*). Once infants habituated to the word-object pairings, the label for one of the objects was switched with the other. In contrast to Stager and Werker's results with consonant minimal pairs, infants in the Curtin, Fennell and Escudero study looked longer at the target object when presented with the mismatching label than with the matching label, suggesting that they were sensitive to the mismatch between the label-object association they were habituated to (e.g., *dit*) and the label presented to them (*deet*) during testing.

Together, these findings indicate an important role for vowels in early lexical representation: vowel identity can influence lexical access of familiar and novel words in 14–15 month-old infants. However, there remains a possibility, suggested by Nespor et al. (2003) and supported by Nazzi (2005) that vowels may be less important in lexical representation than consonants, even though they contribute to lexical identity.

In order to examine this possibility, Mani and Plunkett (2007) compared 15-, 18- and 24-month-old infants' sensitivity to one-dimension changes to the word-medial vowel or the word-initial consonant of familiar words. Vowel changes involved changes to either vowel height or vowel backness, while consonant changes affected the place of articulation or voicing of the consonant. Infants exhibited a symmetry in their sensitivity to even small changes to the vowels and consonants of the familiar words, suggesting that consonants do not have a privileged status over vowels in constraining lexical recognition — at least during early lexical development.

Overall, the data reviewed here can be taken to suggest that infants possess highly detailed representations of vowels in familiar words, given that they are sensitive to small changes to the vowels of these words. But does this mean that infants are sensitive to the differences between any two vowels in their language, or are some vowel changes more or less salient than others? The vowel space of most languages can be organized along specific phonological dimensions such as vowel height, vowel backness, and vowel roundedness. The vowels in a language can be situated on these various dimensions; often with one vowel being minimally distinct from another on a single vocalic dimension. (Such minimal dimensions are usually represented in terms of features. Here we shall simply talk in terms of contrasts on one or another dimension.) In order to explore whether infants are sensitive to minimal changes along these phonological dimensions, the current study presents infants with changes to the height, backness, and roundedness of vowels in familiar words.

In presenting infants with different kinds of changes, the current study also attempts to compare the relative salience of these three vocalic dimensions. Some models of lexical representation suggest that the degree of specification of a particular phonological feature depends on the contrastiveness of the feature in differentiating sounds and words (Lahiri & Marslen-Wilson, 1991; Lahiri & Reetz, 2002). Vowel systems tend to be described in terms of their backness, roundedness, and height. However, cross-linguistically, there is a high degree of correlation between changes to lip-rounding and tongue position (Trubetzkoy, 1939, 1969, p. 100): "Only rarely does it happen that the correlation of lip-rounding or the correlation of tongue position alone has distinctive force." Similarly, Chomsky and Halle (1968, p. 309) point out that "In glides and nonlow vowels, rounding is commonly correlated with the feature 'back', sounds that are back are also round, and sounds that are nonback are nonround." This is true of many languages, including English. In English, all front vowels are unrounded, while a majority of the back vowels are rounded, specifically non-low back vowels, as well as some of the low back vowels. Specification of roundedness is thus largely redundant as far as lexical representations of English words are concerned. Although infants possess adequate phonological specification of vocalic nuclei to distinguish familiar words, infants' representations could still be underspecified with respect to some of the less contrastive vocalic dimensions. Consequently, English infants may be more sensitive to mispronunciations involving changes in vowel height or vowel backness than mispronunciations involving changes in vowel roundedness.

A similar hierarchy of vocalic dimensions is not maintained in infants' production of vowels. Stoel-Gammon and Herrington (1990) suggest that American English vowels are acquired in three stages. The earliest stage consists of the acquisition of /i, u, o, ɑ, ʌ/,[1] comprising of both rounded and unrounded, high and low, and front and back vowels. This stage is usually characterized as the acquisition of corner vowels and mostly tense vowels. Stage 2 consists of the acquisition of /a, ʊ, ɔ, ə/ — by this age infants have mastery of the four corner vowels and all back vowels. The final stage is characterized by the acquisition of the front lax vowels /ɪ, ɛ, e/. While there has been some minor rearrangement of the vowels in different stages of acquisition in recent research, there appear to be no differences in the age of acquisition of vowels exemplifying changes in vowel roundedness, height or backness (Pollock & Keiser, 1990; Selby, Robb, & Gilbert, 2000).

Examination of the errors produced by children with phonological disorders reveals a very different hierarchy to that supported by the distinctive feature-based account. Pollock and Keiser (1990) report that backness (41%) and height errors (33%) were the most frequent, with rounding errors accounting for only 11% of all errors made by their subjects. Interestingly, Nettelbladt (1983) (cited in Goldstein & Pollock, 2000) reports finding more rounding errors in Swedish children (exposed to a language with more rounding contrasts — Swedish has front, round vowels) than has been recorded with English children (exposed to a language with fewer rounding contrasts). This suggests that children are more prone to errors along a dimension that is more contrastive in their language than along a dimension that is less contrastive in a language. Perhaps exposure to a greater variety of changes along a dimension proves too confusing for children with phonological disorders. It is important to point out, here, that most of these studies were conducted on much older children with phonological disorders, exposed to American English dialects, with vowels rather different from standard British English vowels. However, much younger normally developing children have also been found to make more errors along the height

[1] The commonest American English pronunciation of /ʌ/, a stressed [ə], differs from the Southern British English pronunciation [ʌ] used in our experiments. Note that Southern British English [ʌ] is low and back, while American /ʌ/ = [ə] is mid-central.

and backness dimension than others, with almost all investigators reporting errors involving the height of front vowels and neutralization of the contrasts between the low vowels /æ, ɑ, a/ (Bleile, 1989, Leopold, 1947, Menn, 1976).

While the age of acquisition data raises no inequalities in the mastery of vowels exemplifying the roundedness, backness, and height changes in the first stage, production errors made by children do seem to suggest that children are more prone to height and backness errors than roundedness errors. This might predict an alternative ordering of infants' sensitivity to the different mispronunciations presented to them, with infants being more sensitive to roundedness mispronunciations than height and backness mispronunciations. However, we cannot necessarily assume that there is a deterministic influence between infants' ability to produce a vowel and infants' sensitivity to a mispronunciation of that vowel. Infants may be able to produce a vowel accurately but fail to show a mispronunciation sensitivity, or vice versa.

Changes along a vocalic dimension necessarily change the acoustic characteristics of the vowel. These changes can often be quite predictable, with changes in height being correlated to changes in the first formant of the vowel (Joos, 1948), and changes in vowel backness leading primarily to changes to the second formant of the vowel (Ladefoged, 1993). Curtin, Fennell, and Escudero (2006) report that infants show greater sensitivity to some vowel changes ([i] to [ɪ]) over others ([ɪ] to [u]) and argued that infants rely more on the acoustic differences between the vowels than the phonological differences: Curtin, Fennell, and Escudero only analyzed infants' sensitivity to two vowel changes — the current study provides a more comprehensive analysis of the influence of acoustic versus phonological differences by comparing across a larger range of vowel changes and phonological dimensions.

We examine 18-month-old infants' sensitivity to mispronunciations involving small changes to the vowels in familiar words. The study provides a systematic comparison of infants' sensitivity to three different kinds of minimal vowel mispronunciations, testing whether a highly distinctive vocalic dimension, height, is more fully specified than the two correlated phonological dimensions of backness and roundedness.

2 Method

2.1 *Participants*

The participants in this experiment were 59 infants at 18 months ($M = 18.34$ months, Range = 17.6 months to 19.4 months). Fifteen additional infants were tested but were excluded from this study due to fussiness, parental interference, experimenter error or because they did not complete the experiment. All infants had no known hearing or visual problems and were recruited via the maternity ward at the John Radcliffe Hospital in Oxford. Infants came from homes where British English was the only language in use. All parents were asked to complete the Oxford Communicative Developmental Inventory (OCDI; Hamilton, Plunkett, & Schafer, 2000), a British adaptation of the MacArthur CDI.

2.2
Stimuli

The speech stimuli were produced by a female speaker of British English in an enthusiastic, child-directed manner. The audio recordings were made with a solid state compact flash card recorder in a sound-treated, recording booth, using a Sony electret condenser microphone. The audio stimuli were digitized at a sampling rate of 44.1kHz and a resolution of 16 bits and edited using Goldwave v. 5.10 and Wavesurfer for subsequent acoustic measurements.

The stimuli presented to infants were six monosyllabic (CVC) nouns taken from the OCDI. Each infant heard five labels, two of which were correctly pronounced while three were incorrectly pronounced. Almost all mispronunciations resulted in nonwords: three of the mispronunciations used in the experiment resulted in words known to adults but not known to 18-month-olds, as judged by parental reports on the OCDI (*bed* [bɛd] → *bud* [bʌd], *bed* [bɛd] → *bid* [bɪd], and *bus* [bʌs] → *boss* [bɒs]). Table 1 gives a complete list of the words and their corresponding mispronunciations.

The shape of the Southern British English vowel system (see Table 2) does not allow for the same vowel to be mispronounced in three ways to yield minimal height, roundedness, and backness mispronunciations. Consequently, not all words could change along all three dimensions to yield three separate minimal contrasts. Across infants, four words changed in vowel roundedness to yield minimal roundedness mispronunciations [*ball*, *brush*, *bus*, and *dog*]. Four words changed in vowel height to yield minimal height mispronunciations [*ball*, *bed*, *bib*, and *dog*][2]. The number of words known to infants at 18-months and the number of minimal changes to vowels resulting in other legal English vowels limited us to three words that changed primarily in vowel backness [*bed*, *brush*, *bus*]. One word changed in vowel backness and height to yield a greater mispronunciation [*bib*].

Some limitations of the current study should be noted. Due to the constraints imposed by the shape of the English vowel system and the few words known to 18-month-olds, we could not ensure that all changes were equal in degree — for example, some of the changes were larger (from [ɪ] to [a]) than others (from [ɛ] to [a]). We only considered the main changes to any vowel. For instance, the change from [ɔ] to [ʌ] was considered a change in roundedness alone, ignoring the smaller nondistinctive variation in backness. Similarly, the change from [ɛ] to [ʌ] was considered a change primarily in backness, ignoring the smaller change in height. Our reasoning for ignoring this change is that there are not as many contrasts along the height dimension for back vowels as for front vowels. Nor is it obvious that we can equate the height

[2] Due to the greater distribution of vowels spanning the height dimension at the front of the mouth, this vowel space is usually characterized with three levels: high, mid, and low. In this characterization, the change from *bib* to *bab* would be represented as a larger change from high to low, and the change from *bed to bus, and bus to bes* would be characterized as a change in vowel backness and a small change in vowel height. Consequently, the data will be analyzed including and excluding these items, in order to ensure that any sensitivity infants display to changes along the height or backness dimensions are not carried by these items.

distinctions of front and back vowels. Furthermore, changes along the backness dimension are typically accompanied by small changes on the height dimension. Since these limitations could not be avoided in our choice of stimuli, further analyses will attempt to identify the impact of these factors on our results.

Table 1

Durations of correctly pronounced and mispronounced labels

	Height			Backness			Roundedness		
	Label	Duration (ms)	Distracter	Label	Duration (ms)	Distracter	Label	Duration (ms)	Distracter
Correct	Ball [bɔl]	604	Boat	Bed [bɛd]	573	Bike	Ball [bɔl]	604	Boat
Incorrect	Bool [bʊl]	608	Boat	Bud [bʌd]	552	Bike	Bull [bʌl]	611	Boat
Correct	Bed [bɛd]	573	Bike	Bib [bɪb]	447	Book	Brush [brʌʃ]	703	Bread
Incorrect	Bid [bɪd]	514	Bike	Bub [bʌb]	533	Book	Brosh [brɒʃ]	724	Bread
Correct	Bib [bɪb]	447	Book	Brush [brʌʃ]	703	Bread	Bus [bʌs]	700	Boot
Incorrect	Bab [bab]	565	Book	Brash [braʃ]	765	Bread	Bos [bɒs]	696	Boot
Correct	Dog [dɒg]	574	Duck	Bus [bʌs]	700	Boot	Dog [dɒg]	574	Duck
Incorrect	Doog [dʊg]	600	Duck	Bes [bɛs]	684	Boot	Darg [dɑg]	625	Duck
Mean (correct)		549			605			645	
Mean (Incorrect)		572			633			663	

The durations of the correctly pronounced and mispronounced labels are given in Table 1. There was no systematic difference in the overall duration between the correct and mispronounced labels: Height: $t(3) = 1.27$; $p = .29$; Roundedness: $t(3) = 0.4$; $p = .7$; Backness: $t(3) = 0.25$; $p = .8$.

Visual stimuli were computer images created from photographs, with one image for each word. Images were judged by three adults (two of the authors and an independent observer) as typical exemplars of the labeled category.

2.3 Procedure

All infants sat on their caregiver's lap during the experiment facing a projection screen (1.3 m × 0.35 m). Two cameras mounted directly above the visual stimuli recorded infants' eye movements. Synchronized signals from the two cameras were then routed via a digital splitter to create a recording of two separate time-locked images of the infant.

Infants were each presented with five trials. In each trial, infants saw images of two familiar objects, side by side, for five seconds. One of the objects was then named in the carrier phrase *Look! target word!* with either a correct label or a mispronunciation. Onset of the target word began halfway into the trial at 2500 ms. The onset of the target word divided the trial into a prenaming and postnaming phase. Infants saw each object only once during the experiment paired with another distracter object whose label began with the same onset consonant. The target-distracter pairings are listed in Table 1. Again, due to restrictions imposed by the number of words known to 18-month-olds and the number of minimal changes resulting in legal English vowels, distracter objects never appeared as targets. Two of the labels presented to infants were correctly pronounced while three were incorrectly pronounced. Of the three mispronunciations, one altered vowel height, one altered vowel roundedness, and one altered vowel backness. Infants never heard the same object labeled with both an incorrect and a correct pronunciation, nor heard the same object labeled with two incorrect pronunciations. Across infants, targets appeared equally often to the left and to the right. Likewise, correct and incorrectly pronounced words identified left and right targets equally often. Words appeared equally often as correct and incorrect pronunciations across infants. Order of presentation of trials was randomized across infants.

2.4 Scoring

A digital-video scoring system was used to assess visual events on a frame-by-frame basis (every 40 ms). This technique enabled tracking of every single eye fixation. A second skilled coder evaluated the data from 10% of the participants. Coders achieved a high level of agreement, $r = .95$.

This procedure was used to determine the total amount of time infants spent looking at the target (T) and distracter (D) images for the two phases of each trial; before and after the onset of the target word. We then calculated the amount of time infants spent looking at the target (T) over the amount of time infants' spent looking at the target and distracter (T+D) in order to determine the proportion of time infants spent looking at the target—Proportion of Target Looking measure (PTL). As in previous research, it was assumed that the amount of time required by infants to initiate an eye movement was 367 ms (Swingley & Aslin, 2000, 2002). Consequently, analysis of the postnaming phase of the trial was initiated 367 ms after the onset of the target word. This ensures that the analyses only consider changes in infants' looking behavior that can reasonably constitute a response to the spoken word. Systematic increments in infants' PTL across the two phases of the trial can be interpreted as a measure of the child's understanding of the target word (Bailey & Plunkett, 2002; Meints, Plunkett, & Harris, 1999; Schafer & Plunkett, 1998; Swingley & Aslin, 2000).

Similarly, we calculated the difference (t–d) between infants' Longest Look (LLK) at target (t) and distracter (d) images before and after target word onset (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Meints, Plunkett, & Harris, 1999; Schafer & Plunkett, 1998). A difference measure is used to calculate the target preference during each phase of the trial because the longest looks involve only single fixations on target and distracter. As with the PTL measure, a significant increase in infants' preference for the target across the two phases of the trial indicates infants' association of the target label and target object.

Only those trials in which infants fixated both the target *and* the distracter at some point during the trial were included. This criterion excluded a total of 30 out of 347 trials from the analysis.

3 Results

Figure 1 shows the increment in target looking from the pre- to the postnaming phase in each of the pronunciation conditions. There is an increment in looking towards the target when the labels are correctly pronounced and when the labels are mispronounced by vowel roundedness. Conversely, there appears to be no systematic change in target looking from the pre- to the postnaming phase when the target labels are mispronounced either by vowel backness or vowel height.

3.1 *PTL measure*

A 4 × 2 repeated measures ANOVA with the factors naming (prenaming and post-naming) and pronunciation accuracy (correctly pronounced and mispronounced by phonologically minimal changes in backness, height, and roundedness) revealed no significant main effects of pronunciation, $F(3, 56) = 0.3$; $p = .82$, $\eta_p^2 = .01$, or naming, $F(1, 58) = 0.55$; $p = .46$, $\eta_p^2 = .01$, but a significant interaction between naming and pronunciation, $F(3, 56) = 2.904$; $p = .043$, $\eta_p^2 = .135$.[3]

[3] It will be remembered that this analysis considered all trials where infants fixated the distracter and the target at some point during the trial. It could be argued that more conservative trial exclusion criteria should be considered, in which only those trials where infants fixated the target and the distracter in the prenaming phase of the trial were included. This substantially reduces the number of subjects in the analysis. Consequently, the analysis reported throughout the current study imposes the more relaxed exclusion criterion. However, we ran a separate analysis to determine the impact of applying a more conservative criterion. Despite the fewer number of infants in the analysis, we found a significant interaction between naming and pronunciation, $F(3, 48) = 2.997$, $p = .04$.

3.2
LLK measure

Analysis using the LLK measure revealed no significant main effects of pronunciation, $F(3, 56) = 0.3$; $p = .79$, $\eta_p^2 = .02$ or naming, $F(1, 58) = 0.46$; $p = .46$, $\eta_p^2 = .01$, but a significant interaction between naming and pronunciation, $F(3, 56) = 3.514$; $p = .032$, $\eta_p^2 = .145$.

Analysis using both measures indicates the presence of differences in infants' looking behavior between the four pronunciation conditions. Consequently, the effect of mispronunciation was analyzed using separate comparisons between the four pronunciation conditions.

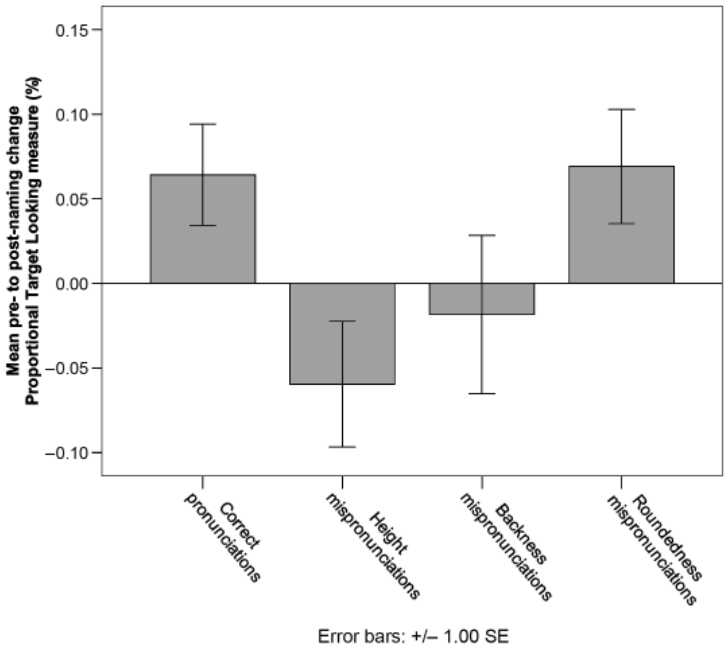

Figure 1
Increments in target looking from the pre- to the postnaming phase in the four pronunciation conditions (PTL measure)

3.3
Correct pronunciations

Planned comparisons revealed a significant increase in target looking from the pre- to the postnaming phase when the target label was correctly pronounced, PTL: $t(1, 58) = -2.142$, $p = .036$, LLK:, $t(1, 58) = -2.273$, $p = .027$. This significant increment in target looking for correctly pronounced labels provides clear evidence that 18-month-olds understand the words used in this experiment.[4]

[4] Note that infants were presented with only one trial per mispronunciation condition and two correct pronunciation trials. This could mean that the significant effect of naming for correct pronunciations was merely due to the greater number of trials per subject. Consequently, we ran a paired samples t-test considering only the first correct pronunciation trial presented to infants. Once again, there was a significant effect of naming for correct pronunciations trials,

3.4
Height

The increase in target looking from the pre- to the postnaming phase when the target label was mispronounced by a phonologically minimal change in vowel height was not significant, PTL: $t(1, 58) = 1.603$, $p = .11$, LLK:, $t(1, 58) = 1.4$, $p = .16$. In addition, there was a significant difference in the increment from the pre- to the postnaming phase between correct pronunciations and mispronunciations caused by a change in vowel height, PTL: $t(1, 58) = 2.657$, $p = .01$, LLK:, $t(1, 58) = 2.582$, $p = .012$. 18-month-olds appear to be sensitive to changes to the height of the vowels in familiar words, insofar as they fail to recognize height mispronunciations as legitimate tokens of the target label. This result suggests that the phonological feature "height" is well-specified in infants' lexical representations.

3.5
Backness

The increase in target looking from the pre- to the postnaming phase when the target label was mispronounced by a change in vowel backness was not significant, PTL: $t(1, 58) = 0.393$, $p = .69$, LLK: $t(1, 58) = 0.64$, $p = .52$. In addition, there was a significant difference in the increment from the pre- to the postnaming phase between correct pronunciations and mispronunciations caused by a change in vowel backness using the LLK measure, $t(1, 58) = 2.02$, $p = .048$, but not the PTL measure, $t(1, 58) = 1.663$, $p = .1$. This result suggests that the phonological feature "backness" is also well specified in infants' lexical representations.

3.6
Roundedness

Planned comparisons revealed a significant increase in target looking from the pre- to the postnaming phase when the target label was mispronounced by a change in vowel roundedness, PTL: $t(1, 58) = -2.049$, $p = .045$, LLK: $t(1, 58) = -1.954$, $p = .055$. The difference in the increment from the pre- to the postnaming phase between correct pronunciations and mispronunciations caused by a phonologically minimal change in vowel roundedness was not significant using either PTL or LLK measures, PTL: $t(1, 58) = -0.11$, $p = .91$, LLK: $t(1, 58) = 0.093$, $p = .92$. These results indicate that 18-month-olds do not appear to be sensitive to changes to the roundedness of the vowels in familiar words, suggesting that the phonological dimension of "roundedness" is underspecified in infants' representations.

3.7
Comparisons between mispronunciation conditions

We also ran separate analyses comparing the effect of naming in the different mispronunciation conditions. Planned comparisons revealed a significant difference

suggesting that the naming effect reported in the main analysis was not caused by the greater number of these trials, PTL: $t(1, 58) = -2.171$, $p = .034$, LLK: $t(1, 58) = -2.24$, $p = .029$. Note that the experiment included two correct pronunciation trials in order to provide a near-equal number of correct and incorrect pronunciations to infants.

in the increment from the pre- to the postnaming phase between mispronunciations caused by changes to vowel height and roundedness, PTL: $t(1, 58) = -2.372$, $p = .02$, LLK: $t(1, 58) = -2.278$, $p = .026$. There was a trend towards a difference in the increment from the pre- to the postnaming phase between mispronunciations caused by changes to vowel backness and roundedness (PTL: $t(1, 58) = -1.4$, $p = .16$, LLK: $t(1, 58) = -1.67$, $p = .09$. Conversely, the difference in the increment from the pre- to the postnaming phase between mispronunciations caused by changes to vowel backness and height was not significant, PTL: $t(1, 58) = 0.71$, $p = .48$, LLK: $t(1, 58) = 0.397$, $p = .69$.

These results support the findings from the earlier ANOVA: 18-month-olds appear to possess well-specified representations of vowel height and vowel backness, but not of vowel roundedness.

3.8
Further analysis

It will be recalled that one of the words (*bib*) was mispronounced by a nonminimal change in height to /bab/ (see note 2). Consequently, we separately analyzed infants' sensitivity to height mispronunciations excluding this item from the analysis. We ran a 2×2 repeated measures ANOVA with naming (pre- and postnaming) and pronunciation accuracy (correct and height mispronunciations) as within-subjects factors. There were no main effects of naming, PTL: $F(1, 32) = 0.5$, $p = .45$; LLK: $F(1, 32) = 0.13$, $p = .7$, or pronunciation, PTL: $F(1, 32) = 0.25$, $p = .6$; LLK: $F(1, 32) = 0.88$, $p = .35$, but there was a significant interaction between naming and pronunciation, $F(1, 32) = 5.774$, $p = .02$; LLK: $F(1, 32) = 4.18$, $p = .04$, indicating that infants were sensitive to minimal height contrasts.

We also ran a separate analysis in order to verify whether infants were sensitive to 1-feature backness mispronunciations of the word *brush* alone.[5] This was in order to ensure that infants' sensitivity to backness mispronunciations was not motivated by the larger vowel changes in the other items: we ignored the smaller change in vowel height in the change from [ɛ] to [ʌ]. In this analysis, we determine whether sensitivity to backness mispronunciations was driven by the additional smaller change in vowel height in the other words presented to infants. If this additional change in vowel height were driving infants' sensitivity to backness mispronunciations, then infants should not show a difference in target preference between correct pronunciations and mispronunciations of *brush* (*brash* is a minimal mispronunciation of *brush*).

We ran a between-subjects analysis of the naming effect in the correct and backness condition using only the data from *brush*-*brash* trials (since infants were never presented with correct and incorrect pronunciations of the same word). Despite the small number of infants who contributed to this analysis, there was a significant difference in the naming effect following correct pronunciations and backness mispronunciations of *brush*, PTL: $F(1, 53) = 4.31$, $p = .04$, LLK: $F(1, 53) = 2.802$, $p = .1$. Taken together with infants' overall sensitivity to vowel changes presented to them in the

5 Although in some accents the change from *brush* to /braʃ/ could be characterized as a two-feature change in height and backness, this is not the case in Southern British English, in which [ʌ] and [a] differ only in backness.

backness condition, these results suggest that infants are also sensitive to backness mispronunciations of vowels. However, since the backness condition is confounded with vowel height changes in three of four cases, any conclusion regarding infants' sensitivity to the minimal mispronunciation of vowel backness must remain tentative.

We also checked to see whether infants were less sensitive to the minimal backness change compared to the other changes in the backness condition. A one-way ANOVA suggested that there was no difference in the naming effect for backness mispronunciations of *brush* and the other mispronunciations in the backness condition by items, $F(1, 3) = 0.73$, $p = .4$, or by subjects, $F(1, 61) = 0.96$, $p = .32$.

3.9
Acoustic analyses

Table 3 reports the acoustic difference between the correct and incorrect pronunciations according to mispronunciation type. This was calculated by measuring the overall spectral difference between the correctly and incorrectly pronounced words at the midpoint of the steady state of the vowel. Overall spectral difference was defined as the Euclidean distance between the power spectra of the two vowels, obtained in Wavesurfer.

Note that we did not use formant measures since analysis of the formants of the vowel cannot provide a single global measure of the acoustic difference between a correct and an incorrect pronunciation across all three mispronunciation types tested in the current study. Changes in vowel height usually lead to changes to the first formant of the vowel. Changes in vowel backness lead to changes to the second formant of the vowel. Conversely, vowel roundedness usually tends to affect second and higher formants.

There were no significant differences between the acoustic characteristics of the different mispronunciation types, $F(2, 11) = 0.83$, $p = .46$, nor was there a significant correlation between mispronunciation type and spectral difference, $r = -.32$, $p = .29$.[6]

Table 2

Vowels used in the experiment

	Front	Back	
	All [−round]	[+round]	[−round]
High	ɪ	ʊ	
Mid	ɛ		
Low	a	ɔ / ɒ	ɑ / ʌ

[6] Note that there was a significant correlation in the variance of the acoustic cues and mispronunciation type when one of the roundedness items (*ball* to /bʌl/) was excluded from the analysis, $r = -.6$, $p = .026$. This correlation suggested that the acoustic differences between correct and mispronunciations decreased from height to backness to roundedness mispronunciations, with the least acoustic difference between correct pronunciations and roundedness mispronunciations.

We calculated a naming effect for each measure of acoustic difference reported in Table 2 by subtracting infants' preference for the target in the prenaming phase from preference for the target in the postnaming phase. We ran a linear regression in order to analyze the proportion of variance in the naming effects of the different mispronunciation types that could be accounted for by the variance in the acoustic characteristics of the mispronunciation (irrespective of the feature contributing to the mispronunciations). The regression confirmed that the naming effects displayed by infants decreased significantly with increase in spectral differences between correct and incorrect pronunciations. The total explained variance ranged from 29% to 46% depending on the looking measure used as the dependent variable, PTL: $F(1, 11) = 4.228$, $p = .067$, $R^2 = .29$; LLK: $F(1, 11) = 8.764$, $p = .014$, $R^2 = .46$. We then analyzed the regression between the naming effects displayed by the different mispronunciation types and the feature contributing to the mispronunciations (i.e., height, backness, and roundedness). Once again, the total explained variance ranged from 37% to 45% depending on the looking measure used, PTL: $F(1, 11) = 8.252$, $p = .017$, $R^2 = .45$; LLK: $F(1, 11) = 6.063$, $p = .034$, $R^2 = .37$. These data confirm that the naming effects correlate significantly with both acoustic and phonological characterizations of the input. There was no suggestion of either acoustic or phonological measures being more or less important, though this might be explained by the correlation suggested between the acoustic and phonological measures (See note 6).

3.10
Effects of vocabulary size

We calculated the mean receptive and productive percentile vocabulary size of infants based on parental OCDI reports. Earlier studies have found no evidence of a relationship between vocabulary size and infants' sensitivity to mispronunciations (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Swingley & Aslin, 2000, 2002). We measured the correlation between infants' vocabulary size and their sensitivity to mispronunciations, as measured by the difference in naming effect between correct and mispronounced labels. As in previous studies, there was no evidence for any correlation either with infants' receptive, $r = .03$, $p = .8$, or productive vocabulary, $r = .07$, $p = .6$.

4 Discussion

Recent research has shown that infants as young as 15 months of age are sensitive to mispronunciations of the vowels in highly familiar and newly acquired lexical items (Curtin, Fennell, & Escudero, 2006; Mani & Plunkett, 2007; Mani & Plunkett, 2008). Similar results have been reported for infants' sensitivity to mispronunciations of consonants in familiar words by as early an age (Ballem & Plunkett, 2005; Mani & Plunkett, 2007; Swingley & Aslin, 2000, 2002). The current paper explored whether infants at 18 months were sensitive to mispronunciations of vowels in familiar words, when the mispronunciations involve changes in height, backness, and roundedness to vowels in familiar words.

The results indicate that 18-month-olds look longer at a target object when the label is correctly pronounced than when the target label is mispronounced on a single dimension: 18-month-olds are sensitive to small changes to vowel identity. This is consistent with research demonstrating that infants are sensitive to mispronunciations of the vowels in familiar words (Mani & Plunkett, 2007). One interpretation of these results would be to suggest that infants possess well-specified representations of the vowels in familiar words, such that a single change along any vocalic dimension impedes recognition of a familiar target label. However, separate comparisons of three mispronunciation conditions indicate that infants were sensitive to mispronunciations of vowel height and vowel backness, but not to mispronunciations of vowel roundedness. A small change to the height or backness of the vowel of a target label hindered infants' recognition of the target, while a change to vowel roundedness did not affect target recognition. This suggests that infants posses well-specified representations of vowel height and vowel backness, but not of vowel roundedness.

Note that not all the height and backness changes presented to infants were minimal changes. However, reanalysis of the results excluding these items yielded precisely the same pattern of results, with infants still showing sensitivity to minimal contrasts involving vowel height and backness.

There are at least three factors that may have an influence on the salience of different vocalic features in lexical representations. These include the articulatory characteristics, the phonological contrastiveness and the acoustic characteristics of the three vocalic dimensions in the language's vowel system. Considering articulatory characteristics first, we know that 5-month-old infants possess cross-modal representations of speech that support an ability to integrate visual and auditory information during speech perception (Kuhl & Meltzoff, 1984). Consequently, the salience of vocalic dimensions may be influenced by the distinctiveness of the visible articulatory cues provided by correct and incorrect pronunciations. This might suggest that roundedness would be a salient vocalic dimension, since rounded and unrounded vowels are marked by distinctive lip-rounding. Vowel height may also be a notable vocalic dimension due to the differences in the amount of lip-opening between high and low front vowels. Finally, vowel backness has the least salient cue due to visible consequences of articulatory distinctions between a front and a back unrounded vowel. A model suggesting integration of visual and auditory features in perception might suggest that roundedness and height would be salient vocalic dimensions, while backness would be less salient. Of course, the current study did not present infants with the facial expressions of the speaker producing correct and incorrect pronunciations. It could be argued that an image of the articulation is necessary for an influence of visual features on perception. However, the current results do not support the view that visible articulatory characteristics influence the degree of specification of different vocalic dimensions in the absence of such information.

In contrast to articulatory factors, the results of the current study are consistent with underspecification models of lexical representation, which suggest that the degree of specification of a phonological feature depends on the level of constrastiveness of this feature in the language's vowel system (Lahiri & Reetz, 2002). Vowel systems of most languages tend to require the contrastive features of height and backness. These are also the features that require specification on more than a binary scale in a number of languages, including English (Landau, 1978). Consequently, most languages may require greater specification of vowel height and vowel backness.

However, front vowels are naturally unrounded, while back vowels are naturally rounded (Ladefoged, 1971). As a result, specification of both vowel backness *and* roundedness may be unnecessary for vowel discrimination in languages like English in which front vowels are always unrounded and a majority of back vowels are rounded. Specification of vowel roundedness may be made further redundant by the relation of vowel roundedness to vowel height: High back vowels tend to have smaller lip openings than low vowels (Landau, 1978). This pattern of featural configuration is consistent with representational underspecification of roundedness in the lexicons of English speakers (Chomsky & Halle, 1968). The results of the current study are also consistent with this underspecification view: 18-month-olds exhibit sensitivity to changes in vowel height and backness, but not roundedness. It would seem that infants learning English as their first language demonstrate precocious sensitivity to the relative contrastiveness of the phonological features underlying their vowel system. However, until further data are obtained, it remains to be seen whether roundedness contrasts are less salient cross-linguistically, irrespective of the contrastiveness of this feature in the infants' language.

Finally, acoustic analysis of the spectral differences between correct pronunciations and mispronunciations provides another perspective on infants' sensitivity to mispronunciations caused by vowel height, but not vowel roundedness. The naming effects displayed by infants regressed significantly with both the acoustic and the phonological measures of the mispronunciations. Acoustic analysis could not pull apart the contribution of acoustic and phonological differences to infants' sensitivity to mispronunciations, possibly due to the significant correlation between the acoustic and phonological differences (see note 6). Our results are compatible with both acoustic and underspecification accounts of the salience of changes in vowel height compared to changes in vowel roundedness.

Table 3

Acoustic differences between correct pronunciations and the different mispronunciation types (as measured by the square root of the sum of the squared difference between the spectra of the correct and incorrect pronunciations)

Label	Height	Backness	Roundedness
Ball	252.0	–	281.2
Bed	264.9	236.1	–
Bib	213.8	244.3	–
Brush	–	242.2	194.2
Bus	–	176.0	208.3
Dog	276.2	–	223.1
Mean	**251.7**	**224.6**	**226.7**

Cross-linguistic studies could more systematically explore the contributions of these two factors to specification of vocalic features in infants' lexical representations.

For instance, roundedness is a more constrastive feature in languages like French, with rounded and unrounded front vowels, and Korean, with roundedness contrasts for both front and back vowels. Future studies might investigate whether roundedness is more specified in Korean infants' lexical representations compared to English infants' lexical representations. Since the acoustic characteristics of the feature change would be more or less the same, greater specification of roundedness in Korean might predict that Korean infants would be more sensitive to roundedness mispronunciations. On the other hand, in order to explore the influence of acoustic information on infants' sensitivity to mispronunciations, future studies could systematically explore whether English infants were more sensitive to greater changes ([ɪ] to [a]) in vowel height than to smaller changes ([ɛ] to [a]). Differences in looking behavior to greater or lesser mispronunciations might provide more support for an acoustic basis to infants' sensitivity to mispronunciations.

Overall, our results provide clear evidence of detailed specification of the vowels in familiar words — even minimal changes to some vowel features constrain lexical access of familiar words as early as 18-months. Previous research has proposed different roles for vowels and consonants in lexical acquisition and lexical access. It is argued that vowels highlight the prosodic characteristics of speech, while the task of distinguishing between different lexical items falls more on consonants (Nespor, Pena, & Mehler: 2003, p. 204). The current study does not directly compare the roles of vowels and consonants in lexical access. However, it does establish that the task of distinguishing between different lexical items does not rely on only consonants — infants possess well-specified representations of vowels in familiar words, and indeed, of vocalic dimensions of contrasts by the end of the second year of life.

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