Using TRACE to Model Infant Sensitivity to Vowel and Consonant Mispronunciations

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Abstract

Very young infants possess a capacity to discriminate contrasts that are not present in their native language. Later in development, they lose this capacity while improving the discrimination of sounds in their native language and progressively tuning their speech sensitivity to increase the phonological specificity of their lexical represenations. Recent evidence suggests a symmetry in infant sensitivity to vowel and consonant mispronunciations of familiar words from early in the second year of life. We investigate this question from a modelling perspective, using a continuous mapping model; TRACE. Our results support Mani and Plunkett's (2007) claim that both vowels and consonants constrain lexical access to familiar words in the infant lexicon. However, TRACE predicts that infants should become increasingly sensitive to onset mispronunciations (usually consonants in English) of familiar words as vocabulary develops, whereas their sensitivity to non-onset (often vowels) mispronunciations should remain relatively stable during the second year of life. Interestingly, this effect is purely driven by the structure and size of the lexicon, as TRACE is not a developmental model.

Keywords: Phonological specificity; Vowels; Consonants; Lexical representation; TRACE model

Introduction

Do vowels and consonants play a similar role in constraining lexical access in infant word recognition? Although it is indisputable that both vowels and consonants are critical for word recognition (*ball* vs. *bell* vs. *tell*), the relative importance of vowels and consonants in the phonological representations of early words has recently come under close scrutiny. For example, Nazzi (2005) describes an experiment demonstrating that consonants are more discriminating than vowels in supporting lexical development at 20 months of age, confirming the view that lexical representations rely mainly on consonants (Nespor, Peña, & Mehler, 2003). In contrast, Mani and Plunkett (2007) have argued for a symmetry in infants' sensitivity to vowel and consonant mispronunciations of familiar words at 18 and 24 months of age, suggesting that both play a role in constraining infant word recognition.

Consonants mispronunciations have been found to influence word recognition from as early as 14 months of age when mispronunciations involve the onset consonant (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Swingley & Aslin, 2000, 2002), and from 19 months of age when the medial consonant is changed (Swingley, 2003). Vowels mispronunciations have not been studied as much as consonant mispronunciations until recently. Swingley and Aslin (2000, 2002) suggest that vowels play a role in phonological representation from 14 months of age. However, this result was based on an analysis of vowel mispronunciations of only two words. More recently, Mani and Plunkett (2007) presented infants with vowel mispronunciations and correct pronunciations of familiar words at 15, 18 and 24 months of age. This detailed study (10 vowel mispronunciations at 15 months of age and 16 vowel mispronunciations at 18 and 24 months of age) confirmed Swingley and Aslin's findings that infants are sensitive to vowel mispronunciations from as early as 15 months of age. In a follow-up study (Experiment 2), Mani and Plunkett (2007) compared directly infants' sensitivity to vowel and consonant mispronunciations of the same familiar words. Infants detected both types of mispronunciations and Mani and Plunkett (2007) found no systematic differences between the two.

Potential explanations of the different pattern of findings concerning the role of vowels and consonants in early lexical representations are many; the tasks are different (Mani and Plunkett (2007) and Swingley and Aslin (2000) used an inter-modal preferential looking task whereas Nazzi (2005) used a name-based categorisation task), the status of lexical items differed (familiar words vs. novel words) and the studies were conducted in different languages (English vs. French). The current study introduces a comparison of infants' sensitivity to vowel and consonant mispronunciations with a widely used computational model of speech perception: TRACE (McClelland & Elman, 1986).

Spoken word recognition is an incremental process involving the elimination of competing candidates that are represented in the individual's mental lexicon. Alternative accounts of spoken word recognition have emphasised the role of cohort competitors (Marlsen-Wilson & Welsh, 1978) or phonological neighbours (Cutler, 1995; Goldinger, Luce, & Pisoni, 1989) in this competition. Attempts to adjudicate between these accounts have argued that both factors impact the resolution of the recognition process. Allopenna, Magnuson, and Tanenhaus (1998) have argued that the TRACE model of speech perception (McClelland & Elman, 1986) provides a satisfactory resolution of the relative role of cohorts and phonological neighbours. In TRACE, a computational listener evaluates speech input against a set of lexical candidates competing for recognition. Allopenna et al. (1998)

found that the time course of spoken word recognition using eye movements can be accurately described by such continuous mapping models. Adults were instructed to move one of four objects that were on a screen, when monitored by an eye-tracker. Along with the referent, three competitors were placed on screen; a cohort competitor (object starting with the same onset and vowel), a rhyme competitor and an unrelated competitor. Using the TRACE model, implementing a forced choice with Luce's choice rule (Luce, 1959) on the four objects present on screen, Allopenna et al. (1998) accurately reproduced the typical pattern of eye-gaze of the participants.

In line with the successful comparison of TRACE with adults' looking behaviour described in Allopenna et al. (1998), we investigate the impact of vowel and consonant mispronunciations using TRACE, in an attempt to mimic the looking behaviour of the infants studied in the two experiments of Mani and Plunkett (2007). The model eliminates the noise of infant performance introduced by inattention, memory failure and variability of individual lexicons and permits a precise evaluation of the impact of the phonological processes inherent in TRACE for infant word recognition. Furthermore, the model allows us to manipulate vocabulary size in a manner that mimics lexical development during infancy, thereby permitting an evaluation of the potential impact of the size and constitution of infant lexicons on their sensitivity to the mispronunciations of familiar words. It is important to note that since TRACE does not possess a developmental aspect, all developmental trends emerging from the model are to be attributed to lexical competition alone.

Experiment 1

The first experiment attempts to simulate Mani and Plunkett's (2007) finding that infants are sensitive to vowels mispronunciations in familiar words from 15 months of age. Mani and Plunkett (2007) used an inter-modal preferential looking task (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987) in which target and distracter objects are presented side-by-side on a projection screen while the target object was named over a loudspeaker using either a correct pronunciation or a mispronunciation. Preference for the target object was used an index of the infants appreciation of an association between the heard label and the visual object.

Method

We used jTRACE (Strauss, Harris, & Magnuson, 2007), a re-implementation of the TRACE model (McClelland & Elman, 1986) in order to simulate Experiment 1 of Mani and Plunkett (2007). We compiled typical lexicons for 15-, 18- and 24-month-year-olds from the British CDI (Hamilton, Plunkett, & Schafer, 2000) (a British adaptation of the MacArthur-Bates CDI, Fenson et al., 1993) using words that are understood by more than 50% of the infants in each age group. The lexicons are specified using data from 50 infants at 15 months of age, 179 infants at 18 months of age and 81 infants at 24 months of age and include 56, 183 and 354 words, respectively.

Recognition time for spoken words is affected not only by the number of phonological neighbours (Cutler, 1995), but also by their frequency (Goldinger et al., 1989). Therefore, we identified individual token frequencies, by extracting word frequencies based on the Manchester corpora (Theakston, Lieven, Pine, & Rowland, 2001) from the CHILDES (MacWhinney, 1991) database, where 12 English children were recorded weekly from 20 to 36 months of age.

Given the large size of the infant lexicon at 24 months of age, many of the phonemes needed to represent the different words were not encoded in the original TRACE model (McClelland & Elman, 1986) nor in its re-implementation (Strauss et al., 2007). Therefore, we added feature values for all phonemes used in the infant's lexicon.[1] Table 1 reproduces the feature value of all phonemes used in the simulations. Long vowels such as uː, iː, əː, ɔː, ɛː are implemented as being twice as long as their respective short counterparts u, i, ə, ɔ, ɛ, while keeping the same feature values. All words in the lexicon were encoded using the IPA phonemes listed in Table 1, using British English pronunciation. Vowel and consonant mispronunciations were encoded using their phonetic description reported in Mani and Plunkett (2007).

Table 1: Phoneme feature values used in the simulation; Pow=Power, Voc=Vocalic, Diff=Diffuse, Acu=Acute, Cons=Consonantal and Voi=Voiced

Phoneme	Pow	Voc	Diff	Acu	Cons	Voi	Burst
p	4	1	7	2	8	1	8
b	4	1	7	2	8	7	7
t	4	1	7	7	8	1	6
d	4	1	7	7	8	7	5
k	4	1	2	3	8	1	4
g	4	1	2	3	8	7	3
s	6	4	7	8	5	1	-
ʃ	6	4	6	4	5	1	-
r	7	7	1	2	3	8	-
l	7	7	2	4	3	9	-
a	8	8	2	1	1	8	-
i	8	8	8	8	1	8	-
u	8	8	6	2	1	8	-
ʌ	7	8	5	1	1	8	-
w	7	7	7	2	2	8	-
ʊ	8	8	7	3	1	8	-
f	6	4	7	3	5	1	-
ɒ	7	8	2	2	1	8	-
ə	7	8	4	1	1	8	-
ɪ	8	8	7	6	1	8	-
ɑː	8	8	2	2	1	8	-
θ	6	4	7	4	5	1	-
n	7	6	7	7	4	8	-
m	7	6	7	2	4	8	-
ð	6	4	7	4	5	8	-
e	8	8	7	7	1	8	-
z	6	4	7	8	5	8	-
v	6	4	7	3	5	8	-
ʒ	6	4	6	4	5	8	-
j	7	7	8	8	2	8	-
ɛ	8	8	4	6	1	8	-
h	6	4	4	1	5	1	-
ŋ	7	6	2	3	4	8	-
ɔ	8	8	4	2	1	8	-

Correctly pronounced words and mispronounced words are presented to the model and activation levels of two competitors (the target and a distracter) are monitored. We adopt the

[1] Thanks to Ōiwi Parker-Jones for help in assigning feature values for phonemes not present in the original TRACE model.

same linking hypothesis as Allopenna et al. (1998), in order to map the activation levels to fixation probabilities. We assume that fixation probability to the image i is a direct function of the probability that its associated label is the target, given the pronounced word. Moreover, the probability that image i is the target is determined by comparison of the activation levels of the labels associated with the other potential targets. Following Allopenna et al. (1998), activation levels (a) are then transformed into response strengths following Luce (1959). Given the high salience of the images, we assume that total looking time is split entirely between the target and distractor objects, enabling us to convert the response strengths into response probabilities using the Luce choice rule. The probability of looking to the target becomes:

$$p_{target} = \frac{e^{ka_{target}}}{e^{ka_{target}} + e^{ka_{distractor}}} \quad (1)$$

where k is a free parameter determining the amount of separation between units of different activations (value set to $k = 2$). All other parameters used in jTRACE were set to their default values. Proportion of looking times to the target and distracters are reported as the average over 100 processing cycles starting with the onset of the pronounced word. No attempt was made to match the actual time course of the infants' looking behaviour.

Table 2 presents the stimuli used in Experiment 1 by Mani and Plunkett (2007) and in the current simulation. The stimuli used for 15 months old were slightly different in order to accommodate to their smaller vocabularies but maintained the same constraint that targets and distracters had the same onsets.

Table 2: Correctly pronounced and mispronounced labels presented to infants at 18 and 24 months, as in Experiment 1 of Mani and Plunkett (2007)

Correct pronunciation	Incorrect pronunciation	Distracter
Ball	Bal	Bed
Bed	Bod	Ball
Bib	Bab	Boot
Book	Bik	Bus
Boot	Bot	Bib
Bread	Brod	Brush
Brush	Brish	Bread
Bus	Bis	Book
Dish	Dush	Doll
Dog	Dig	Duck
Doll	Dill	Dish
Duck	Dack	Dog
Milk	Marlk	Moon
Moon	Marn	Milk
Sock	Souk	Sun
Sun	Sen	Sock

Results

Table 3 displays the proportion of looking times at the target produced by the model. The model's response probabilities match the pattern of infant looking preferences; target preferences are greater when the referent is correctly pronounced than when the medial vowel is changed (15 months of age; $p < 4 \cdot 10^{-4}$: 18 months of age; $p < 10^{-5}$: 24 months of age; $p < 10^{-4}$), indicating that vowel identity plays a contributing role in constraining auditory word recognition in jTRACE when using lexicons representative of 15–24 month old infants. A naming effect is significant in both conditions across all age groups; the model predicts looking times to the target greater than chance, indicating that the referent is recognised despite the mispronunciation (all p's $< 3 \cdot 10^{-4}$). No age effect was found.

Table 3: Percentage of looking time spent on target for correctly pronounced and mispronounced labels presented to jTRACE .

	15m	18m	24m
Correct	74.60 (1.76)	74.82 (1.62)	73.10 (1.61)
Vowel misp.	63.92 (7.63)	62.57 (8.53)	61.21 (7.95)

Experiment 2

In a second simulation, we aim to clarify the relative importance of vowel and consonant mispronunciations in familiar words, by modelling the second experiment of Mani and Plunkett (2007). In this study, we compare looking times to the target when it is pronounced correctly, when the medial vowel is changed and when the onset consonant is changed.

Method Table 4 presents the stimuli used in Experiment 2, matching those used in the second experiment in Mani and Plunkett (2007). Whereas all stimuli belong to the typical lexicons of 18 and 24 month old infants, *bib, bike, boot, bus, coat* and *keys* were added to the 15 month old jTRACE lexicon, even though they are only known, according to the British CDI (Hamilton et al., 2000), by less than 50% of the infants at that age.

Results

Table 5 reports the proportion of time looking to the target in the different conditions; when the referent is correctly named, when the medial vowel is changed and when the onset consonant is changed. For all age groups, looking times at the target were longer for correct pronunciations compared to mispronunciations, verifying the contributing role of vowels and consonants in constraining auditory word recognition in jTRACE when using representative infant lexicons. Target preference is greater for correct pronunciations than for vowel mispronunciations (15 months of age; $t = -3.5483$, $p = 0.0032$: 18 months of age; $t = -4.5182$, $p < 5 \cdot 10^{-4}$: 24 months of age; $t = -5.4029$, $p < 10^{-4}$). Similarly, simulated looking times are longer for correct pronunciations than consonant mispronunciations (15 months of age; $t = -2.8149$,

Table 4: Correctly pronounced and mispronounced labels presented to infants in Experiment 2 of Mani and Plunkett (2007). Note that targets and distracters have the same onset consonants, so that onset consonants alone cannot be used to identify the target.

Correct pronunciations	Mispronunciations		Distracter
	vowel	consonant	
Ball	Bule	Gall	Bear
Bib	Bab	Dib	Boot
Bed	Bud	Ped	Book
Bus	Bas	Pus	Bike
Cat	Cart	Gat	Cow
Cup	Cep	Gup	Car
Dog	Doog	Bog	Duck
Keys	Kas	Tees	Coat

Table 5: Percentage target looking (SD) for correctly pronounced and mispronounced labels presented to jTRACE.

	15m	18m	24m
Correct	73.53 (3.13)	73.62 (2.98)	73.69 (2.96)
Vowel misp.	63.00 (7.79)	61.39 (7.10)	60.07 (6.48)
Cons. misp.	68.80 (3.58)	65.84 (5.18)	60.94 (5.23)

$p = 0.0138$: 18 months of age; $t = -3.6826$, $p = 0.0025$: 24 months of age; $t = -5.9972$, $p < 10^{-4}$).

A comparison of target preferences between vowel and consonant mispronunciations did not reveal any statistical differences (15 months of age; $t = -1.9126$, $p = 0.0765$: 18 months of age; $t = -1.4414$, $p = 0.1715$: 24 months of age; $t = -0.294$, $p = 0.773$). These simulation results confirm Mani and Plunkett's (2007) claim that there is a symmetry in infants' sensitivity to vowel and consonant mispronunciations as early as 15 months of age.

Closer examination of the results suggests an asymmetry between the sensitivity to vowel and consonant mispronunciations may be present for younger age groups. An age effect analysis (multiple comparison procedure) revealed no effect for correct pronunciations ($F = 0.0057$, $p = 0.9944$), nor for vowels ($F = 0.3388$, $p = 0.7165$). However, the analysis revealed a robust effect for consonants mispronunciations ($F = 5.6443$, $p = 0.0109$). Note that, in the model, the only factor that varies with age is the size of the lexicon itself. This finding predicts that infants should become increasingly sensitive to consonants mispronunciations as their lexicon grows in size. No such change in sensitivity is predicted for vowel mispronunciations over the lexicon range explored in this model.

We also performed a statistical analysis in order to determine whether an effect of naming was observed for mispronunciations as well as correct pronunciations. For all age groups, target looking was significantly greater than chance (50%), for vowel mispronunciations (15 months of age; $p = 0.0022$: 18 months of age; $p = 0.0026$: 24 months of age; $p = 0.0032$) and for consonant mispronunciations (15 months of age; $p < 10^{-5}$: 18 months of age; $p < 10^{-4}$: 24 months of age; $p < 6 \cdot 10^{-4}$). Mispronunciation naming effects were not found in Mani and Plunkett (2007). However, Swingley and Aslin (2000) report a mispronunciation naming effect for infants between 18 and 23 months of age (73% of looking times at target for correctly pronounced labels and 61.3% for mispronunciations). Figure 1 provides a graphical comparison of Swingley and Aslin's (2000) data to the simulation results. The mispronunciations reported in Swingley and Aslin (2000) correspond to the aggregation of four consonant mispronunciations and two vowel mispronunciations. The close

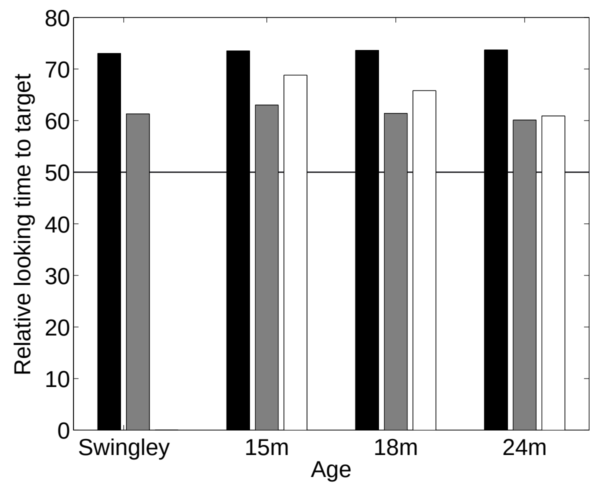

Figure 1: Target preferences for correct pronunciations (black bars), vowel mispronunciations (grey bars) and consonant mispronunciations (white bars). Notice the close agreement of the TRACE simulations with Swingley et al.'s (2000) data for 18 to 23 month-year olds where all mispronunciations are aggregated into the grey bar.

agreement between the simulation results and experimental data suggest that, like the infants, jTRACE can identify the target referent in a forced choice task when the target is mispronounced. jTRACE succeeds over a broad range of mispronunciation types and vocabulary sizes when the name of the distracter has the same consonant onset as the target. It should be noted that this constraint did not hold in the Swingley and Aslin (2000) study where targets and distracters had different onsets.

Discussion

We have investigated the impact of vowel and consonant mispronunciations on lexical access to familiar words in infancy from a modelling perspective. A comparison of simulation results to experimental data suggests that the TRACE model, when supplemented with the Luce choice rule, appropriately captures infants' looking preferences in a forced choice interpretation of the intermodal preferential looking task. The model, as with the infants, showed greater target looking when the target is correctly pronounced than when it is mispronounced. Looking times at the target in the model did not differ significantly when the mispronunciation involved an onset consonant change and when it involved a medial vowel change for all age conditions, thereby mimicking the symmetry in infants' sensitivities to vowel and consonant mispronunciations in familiar words present from an early age (Mani & Plunkett, 2007). However, the simulations predict that infant sensitivity to vowel and consonant mispronunciations exhibit different development trajectories; while age has no impact on target preferences for correct pronunciations and vowel mispronunciations, a robust age effect is found for consonant mispronunciations. Furthermore, the simulation results suggest that, despite a sensitivity to mispronunciations, looking times at target exceeded chance, indicating the presence of a naming effect as reported by Swingley and Aslin (2000) (also reported by Bailey and Plunkett (2002) and Ballem and Plunkett (2005)). This set of results has important implications for theories of lexical competition in infancy that we discuss below.

In the continuous mapping model used, TRACE, competition occurs at the levels of phonemes and words. The model contains no semantic associations nor semantic representations of any kind. As a consequence, the patterns of findings observed in Mani and Plunkett (2007) can be explained, computationally in terms of phonological competition alone. In that account, upon hearing a word, its phonological content is compared to the phonological content associated with both pictures presented to the infant; the target and the distracter. Words in their lexicons compete at the level of their *phonological* overlap. Although semantic information may be accessed shortly after hearing the word, as suggested by Swingley and Fernald (2002), no semantic content is required in order to explain the effects of vowel and consonant mispronunciations and the naming effect observed in infants.

Different age groups are modelled by coding their typical lexicons. Word frequencies, phonological features and all other parameters are kept constant across lexicons Therefore, age effects in the model are driven solely by the different set of competitors (the infant's lexicon) at 15, 18 and 24 months of age. As the size of the lexicon increases, the set of competitors increases, thereby impacting directly the set of cohort competitors. Note that for these relatively small lexicons the probability that a lexical entry has a phonological neighbour remains quite small. Potential lexical candidates in TRACE are activated as the input unfolds over time. Thus, the initial portion of the word is important for activating potential lexical candidates as proposed by the cohort account (Marlsen-Wilson & Welsh, 1978). Table 6 displays the number of cohort competitors for different onset consonants used in Experiment 2, in the typical lexicon at 15, 18 and 24 months of age. The number of potential lexical competitors increases dramatically in this age range. For example, the number of *t*-onset words increases by a factor 4 in the three month period from 15 to 18 months, *p*-onset words increases by a factor 20 between 15 and 24 months and the first *g*-onset words appear first at 18 months. In the model, the dramatic increase in the number of words around the time of the vocabulary spurt impacts directly the phonological sensitivity to onset consonant mispronunciations, even in the absence of any change in the semantic representations of words in the developing lexicon.

Table 6: Number of cohort competitors for different onset consonants used in Experiment 2, at 15, 18 and 24 months of age.

Onset phoneme	15m	18m	24m
b	15	31	35
d	5	8	13
g	0	3	6
k	7	12	16
p	1	5	20
t	5	22	25

In contrast, sensitivity to vowel mispronunciations seems to be unchanged by the size of the lexicon, over the age range considered. TRACE fails to identify an exact referent for the mispronounced word and compares both words associated with the target and distractor to the input word, in terms of overall phonological overlap. The size of the lexicon and the number of competitors have no direct impact on the head-to-head comparison of the target and distractor. Furthermore, once the main effect of cohort competition is eliminated, only subtle effects of neighbourhood activation can be distinguished. The forced choice procedure, implemented through the Luce rule in the model, enhances the match of the phonologically neighbouring vowel mispronunciation to the target. Hence, vowel mispronunciation effects are relatively insensitive to changes in vocabulary size.

In summary, the sensitivity to onset consonant mispronunciations is directly influenced by the number of cohort competitors, a by-product of the increasing size of the lexicon. The sensitivity to medial vowel mispronunciations is, in contrast, a subtle effect of the co-activation of neighbourhood words enhanced by the forced choice procedure. In this respect, we suggest that the presence of a sensitivity to non-onset changes need not be attributed to the fact that it is a vowel change. Any change to non-onset phonemes should have a similar impact. This prediction is supported by findings that infants are also sensitive to medial consonant mispronunciations (Swingley, 2003). As discussed above, the number of cohort competitors directly impact the sensitivity to onset mispronunciations. A language with a substantial incidence of onset vowel words should display a strong sensitivity to onset vowel mispronunciations which increases with age.

The implementation of TRACE for studying phonological sensitivities and lexical competition can easily be extended to the study of speech sensitivities in different languages and at different ages. Moreover, the implementation of the Luce rule allows for a direct comparison to infants' looking preferences in a visual world task. In the present study, we have shown that infant sensitivity to word mispronunciations, as indexed by preferential looking, can be explained purely in terms of phonological competition. The conditions of competition implemented in the model were quite severe insofar as the labels for the target and distracter objects always had the same onset consonants. Investigation of the effects of relaxing this constraint would enable a more direct comparison to other experiments investigating infant mispronunciation sensitivities (Swingley & Aslin, 2000, 2002; Bailey & Plunkett, 2002; Ballem & Plunkett, 2005).

The simplifying assumptions adopted in the current implementation also maintained word token frequencies across age conditions. The model would also allow an evaluation of the impact of token frequency on mispronunciation sensitivity, and the model's sensitivity to mispronunciations of recently acquired words and/or minimal pairs. A comparison of vowel and consonant mispronunciations of recently acquired words that form minimal pairs would permit a computational investigation of Nazzi's (2005) claim that consonants are more salient for lexical acquisition than vowels.

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