Roburstness: Quantifying Robustness of the /t/—/k/ Contrast in Children and Adults

By: Allison A. Johnson

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ABSTRACT

Children develop speech gradually throughout childhood, and they continue to refine articulatory movements and phonological productions even after they have acquired a sound or sound contrast. In research and clinical practice, speech is most often characterized using coarse-grained transcription methods; however, broad phonemic classifications or simple judgments of correct/incorrect fail to capture variations in productions. Measureable sub-phonemic differences in children’s speech, such as covert contrasts, undifferentiated lingual gestures, or intermediate productions, are difficult to classify using only transcription, but they have been quantified using fine-grained acoustic or perceptual measures. These subtle differences have important clinical implications in diagnosis of speech sound disorders, developing focused treatment approaches, and determining prognosis for therapy.

Many studies in phonetics have searched for acoustic correlates to characterize speech sounds or phonetic dimensions. The present study directly compared two gradient-scale, central measures—an acoustic measure (Centroid) and a psychoacoustic measure (Peak ERB)—in their utility for quantifying robustness of the /t/—k/ contrast in adults (n = 21) and 2-3-year-old children (n = 163). For adults, both measures were highly successful in differentiating /t/ and /k/, but Centroid was significantly better than Peak ERB for classifying productions in back-vowel contexts. Similar results were found for the children. There was also an interaction effect of target consonant in front-vowel contexts: Centroid better differentiated /t/ and /k/ when the target consonant was /t/, but Peak ERB better differentiated /t/ and /k/ when the target consonant was /k/.

Overall, children showed a less robust contrast compared to adults, even for productions transcribed as correct. These findings provide further evidence that children acquire speech gradually and continue to refine productions even after sounds are considered acquired. For children’s productions that were transcribed as correct, the wide range in robustness of contrast highlights the importance of supplementing transcription with fine-grained measurements to capture developmentally relevant sub-phonemic differences in children’s speech. Limitations of the study and future directions are discussed.

CHAPTER ONE
Introduction

Phonological development is a gradual process, beginning in the first year of life and continuing throughout childhood. During the course of development, acquisition and mastery of speech sounds vary both among children (i.e., some children produce sounds earlier than others) and across sounds (i.e., certain sounds are typically mastered before others). During puberty, children develop finer neuromuscular control, and the lower face, jaw, tongue, and lips grow closer to adult-like proportions, contributing to systematically more adult-like speech productions (Kent, 1976; McLeod & Bleile, 2003; Cheng et al., 2007). Even though young children's productions are not completely adult-like, according to normative data for English-speaking children, most speech sounds are *mastered* (produced accurately >95% of the time) before age nine, and the majority are *acquired* (produced accurately >90% of the time) by age five (Smit et al., 1990).

Some children develop speech more slowly than others. These children may have sufficient delays or deviations compared to age-related standards to be considered speech sound disorders (SSDs). SSD is a broad term encompassing impairments in perception, production, and/or phonological representations of speech sounds that impact speech intelligibility (e.g., Bernthal, Bankson, & Flipsen Jr., 2013). SSDs can be motor-, structural-, or sensory-based in etiology, arising from known medical conditions or syndromes (e.g., apraxia, dysarthria, cleft palate, hearing impairment, auditory processing disorder). In a majority of cases, however, impairments are functional in etiology, arising from unknown causes (National Institute on Deafness and Other Communication Disorders [NIDCD], 2010; NIDCD, 2006; Gierut, 1998). Speech-language pathologists (SLPs), especially those based in school settings, report that children with speech impairments constitute a major portion of their clinical caseloads (Gierut, 1998; Joffe & Pring, 2008). Prevalence estimates of speech delay in children range from 2-25%, though most estimates hover around 5-10% (Law, Boyle, Harris, Harkness, & Nye, 2000). Children with SSDs are at heightened risk for reading and writing difficulties, and persistent reduced speech intelligibility interferes with an individual's social relationships, academic achievement, and vocational security (McCormack, Harrison, McLeod, & McAllister, 2009).

Reliable identification of SSDs is a critical first step in alleviating the long-term consequences of reduced speech intelligibility. Decisions about articulation accuracy and the presence (or absence) of SSDs are generally made using transcription, both clinically and in research studies (e.g., Smit et al., 1990). An auditory-perceptual judgment of 'correct' or 'incorrect' is made by a trained listener about the speaker's productions. Children are diagnosed with SSDs if they produce a significantly greater number of consonants incorrectly than peers of the same age and sex in a connected speech sample and on standardized, norm-referenced assessments of articulation, which typically include single-word productions. During therapy, clinicians also employ judgments of "correct" and "incorrect" to evaluate a child's productions, and once a designated criterion is met (e.g., 9/10 productions transcribed as 'correct' in multiple phonological contexts), the child is said to have acquired that phoneme.

Although transcription provides a relatively quick and ecologically valid method for describing children's productions, there are critical shortcomings to these binary, categorical, perceptual judgments. Children's developing productions do not proceed categorically from one sound to another; rather, speech sounds are progressively refined as articulatory movements become more practiced and precise over time (Edwards, Gibbon, & Fourakis, 1997; Hewlett & Waters, 2004; Scobbie, Gibbon, Hardcastle, & Fletcher, 2000). The transcription system imposes a categorical classification system on a continuously variable articulatory-acoustic signal, and adults' categorical judgments may be inadequate to characterize the gradual refinement of speech productions during children's acquisition period (Gibbon, 1990; Gibbon, 1999; Hewlett, 1988; Munson et al., 2010).

When SLPs and researchers transcribe the speech of children with SSDs, they are unlikely to distinguish within-category differences in productions that vary acoustically. Even narrow transcription (i.e., using diacritics to supplement phonemic decisions) does not always provide an adequate means to distinguish sounds along a continuum of productions, which may include intermediate productions or covert contrasts. Intermediate productions are perceptually and acoustically between two categories, making them difficult to classify using either perceptual or acoustic methods. Covert contrast, or incomplete neutralization, refers to a sub-phonemic difference: two sounds are transcribed using a single phonemic symbol, though there is a measurable acoustic or articulatory difference between them which may or may not be perceptible (e.g., Forrest, Weismer, & Hodge, 1990; Li, Edwards, & Beckman, 2009; Macken & Barton, 1980; Maxwell & Weismer, 1982; Munson et al., 2010; Tyler, Figurski, & Langsdale, 1993). Characteristics of sub-phonemic differences and intermediate productions are lost using a transcription system, even when children are consistently producing measurable articulatory or acoustic distinctions between sounds (Gibbon, 1990). Losing information about these subtle variations reduces precision in profiling production skills and may prevent a fully informed clinical approach. Children who consistently produce covert contrasts progress faster through therapy than children who produce no contrast (Tyler et al., 1993), suggesting that sub-phonemic differences in production reflect underlying knowledge of phonemic contrasts, which facilitates learning during treatment. One viable solution to more accurately describe subtle differences in children's productions would be to use a gradient acoustic measure in conjunction with subjective impressions of speech sounds.

The present study will focus on the place-of-articulation contrast for stop consonants /t/ and /k/. This contrast is produced relatively early in the typical sequence of phonological development, and these sounds have a significant affect on intelligibility due to their high frequency in English. According to normative data for speech sound acquisition (using a 90% criterion), word-initial /t/ is acquired by age three, and word-initial /k/ by age four (Smit et al., 1990). These norms are clinically relevant as they constitute the recommend ages by which children should have mastered these sounds. If children are delayed, assessment and intervention may be warranted.

Many young, typically-developing children exhibit the phonological process of velar fronting (substituting [t] for /k/, as in "tup" for cup), but persistent velar fronting may be indicative of a speech delay or disorder. Unfortunately, there is little agreement in the consonant acquisition literature regarding the exact age of mastery for each speech sound. These variations in reported ages are due to differences in samples (e.g., age range of children; exclusion criteria of participants), criterion for determining acquisition (e.g., 75%, 90%, or 100% accuracy may constitute acquisition), and/or methods of collecting speech data (e.g., sounds in spontaneous speech or imitation; sounds in isolation or connected speech). Another reason there are differences is that normative studies in the consonant acquisition literature rely solely on transcription of consonants as correct or incorrect

Data based on coarse-grained transcription methods may be unsuitable for describing subtle differences in children's productions while they are refining articulation abilities. For example, Todd, Edwards, and Litovsky (2011) found that even when /s/ and /ʃ/ productions from children with cochlear implants were transcribed as "correct," fine-grained analyses showed significantly decreased spectral contrasts compared to correct productions by peers with normal hearing. Furthermore, these acoustic differences had perceptual consequences: /s/- and /ʃ/-initial words produced by children with cochlear implants were found to be less intelligible than the same words produced by peers with normal hearing (Kristensen, 2015). Nicholson, Munson, Reidy, and Edwards (2015) showed that the contrast between correct /s/ and /ʃ/ productions increased with age when fine-grained measures were used. Reidy (2015) found that spectral analysis of the /s/—/ʃ/ contrast in English-speaking adults and typically developing 2- to 5-year-old children revealed differences in anticipatory coarticulation in consonant-vowel sequences between young children and adults, even for productions that were transcribed as correct. Hewlett (1988) showed varying levels of coarticulation and differentiation of /t/ and /k/ productions between adults, children with typical development, and a child with phonological disorder when fine-grained measures were used, even for productions that had been transcribed as correct. Nittrouer (1995) found that 7-year-old children whose transcribed productions showed a clear contrast between /s/ and /ʃ/, spectral analyses revealed that their productions were less differentiated than adults' productions. However, these children produced /t/ and /k/ with spectral contrasts similar to the adults, highlighting the fact that some contrasts are developed earlier than others, and that children produce less robust contrasts initially after a contrast is considered acquired based on transcription.

Much of this work on the gradual acquisition of speech sounds has focused on the English /s/— /ʃ/ contrast. This contrast has been conducive to this research for two reasons: it is a relatively late-acquired contrast, and it can be well-differentiated by a single acoustic or psychoacoustic parameter (e.g., centroid) The focus of this study is on the acquisition of the

/t/—/k/ contrast. This contrast is of interest because it is acquired earlier, so it may be of more diagnostic importance. However, the /t/—/k/ contrast is also more difficult to differentiate with a single acoustic parameter, particularly in certain phonological contexts. The dorsal stop /k/ may be fronted before front vowel contexts, a process called velar softening or velar palatalization (Guion, 1998; Stevens, 1998). Children with and without phonological disorders also show varying degrees of coarticulation of /k/ before front vowels, making differentiation of /t/ and /k/ in front-vowel contexts more difficult (e.g., Hewlett, 1988). Using spectral analyses and individual regression analyses to quantify the /t/—/k/ contrast in 2-3-year-old children, it may be possible to detect subtle differences in speech productions occurring during the typical course of development, even before a sound is considered "acquired" based on traditional, coarse-grained transcription.

Acoustic information in the release burst (specifically, the frequency spectrum) varies as a function of place of articulation (e.g., Harrington, 2013; Stevens, 1998). Specifically, the size and shape of the vocal tract in front of the constriction contributes to spectral information in the sound produced (Jongman, Wayland, & Wong, 2000). Alveolar stop consonants have a relatively short vocal tract length in front of the constriction, resulting in burst frequencies ranging from approximately 2,500 - 4,000 Hz. Comparatively, velar stops have a longer vocal tract length, resulting in lower burst frequencies, ranging from about 1,500 - 2,500 Hz (Reetz & Jongman, 2008; Stevens, 1998). Phonological context also affects spectral information in the consonant produced, especially for /k/, which coarticulates extensively with the following vowel (i.e., if the following vowel is a front vowel, burst frequencies will be higher than if the following vowel is a back vowel) (Guion, 1998; Stevens, 2000).

For decades, researchers in phonetics have searched for invariant acoustic correlates to characterize individual speech sounds or phonetic dimensions, such as place- or manner-of-articulation. One type of parameterization that has been largely successful in differentiating place-of-articulation in stop consonants and sibilant fricatives is *spectral moments* analyses (Forrest et al., 1988; Harrington, 2013; Jongman et al., 2000). Spectral moments are derived from statistical moments: each spectrum is treated as a random probability distribution from which mean, variance, skewness, and kurtosis (the first four spectral moments) can be computed. These moments capture information about local and global characteristics of the spectrum, including overall concentration, range, tilt, and peakedness of the energy distribution.

The first spectral moment, spectral mean or Centroid frequency, represents the frequency at which energy in the spectrum is primarily concentrated, or the average concentration of energy. As an obstruction in the vocal tract moves forward, the centroid frequency is expected to increase. Spectral variance (or spectral standard deviation if the square root is taken) represents the range in energy concentration, or how energy is distributed across frequencies. Some speech sounds, such as /b/ and /d/ have relatively diffuse spectra, which could be differentiated by the second spectral moment. However, studies such as Forrest et al., (1988) showed that the second moment did not add to the discriminability of stop consonants, and it has largely been excluded from spectral moments analyses of voiceless stop consonants since, though see Nissen and Fox (2009) for counterexample. Skewness, the third spectral moment, measures asymmetry in energy distribution of the spectrum, or the spectral tilt. If energy is concentrated in the lower frequencies, the spectrum will have a negative tilt and positive skewness. The fourth spectral moment is kurtosis. Positive kurtosis occurs when energy in the spectrum is concentrated in a peak, whereas negative kurtosis reflects a relatively flat distribution.

There has been much research using spectral moments to distinguish sibilant fricatives (e.g., Forrest et al., 1988; Hazan & Baker, 2011; Holliday, Reidy, Beckman, & Edwards, (2015); Li et al., 2009; Maniwa & Jongman, 2009; Nissen & Fox, 2005; Shadle & Mair, 1996). Many research studies have also used spectral moments to characterize place-of-articulation for voiceless stops in adults and children (e.g., Forrest et al., 1988; Forrest et al., 1990; Marin, Pouplier, & Harrington, 2010; Nissen & Fox, 2009; Strömbergsson, Saliv, & House, 2015). This research consistently shows relatively high classification accuracy based on spectral moments, especially the first moment, Centroid frequency.

Although frequency components are often described on a linear scale in terms of Hz, the Equivalent Rectangular Bandwidth (ERB)-scale is another useful scale that can be used to describe sounds in a more psychoacoustically relevant manner (e.g., Glasberg & Moore, 1990, Moore & Glasberg, (1983); Moore and Glasberg, (1996); Moore, Glasberg, & Baer, (1997). The ERB-scale is a psychoacoustic scale that models how the human auditory periphery logarithmically compresses the Hz scale. On this scale, the frequency axis reflects the average value of equivalent rectangular bandwidth of the auditory filter. Each unit increase on the ERB-scale corresponds to a distance of approximately 0.89mm on the basilar membrane (Moore, 2013). While conceptually similar to the Bark scale (see Zwicker, 1961, Zwicker & Terhardt (1980); for examples in consonant classification literature, see Forrest et al., (1988), Jongman et al., 2000), the ERB-scale is considered a more accurate representation of the auditory filter because at lower frequencies, as center-frequency of the bandwidth decreases, the slope of the ERB function also decreases whereas the slope of the Bark scale remains relatively linear (Moore, 2013). The ERB-scale has been used successfully in classifying fricatives (e.g., Nicholson et al., 2015; Nissen & Fox, 2005; Reidy, 2015), and will be explored in this study as a potential alternative to the linear Hz-scale that may better correspond to the representation of frequency within the auditory periphery.

One agreed-upon issue with using acoustic measures to characterize the gradual acquisition of a contrast is that there are no meaningful absolute values. Therefore, it is necessary to develop way to quantify the acoustic (or psychoacoustic) differences between the two sounds in a contrast at the individual speaker level, rather than classifying single sounds or dimensions. Holliday and colleagues (2014) explored several measures to quantify robustness of contrast and describe differences within and across /s/ and /ʃ/ productions that were transcribed as correct in both children (2-5-years old) and adults. Four components were explored to quantify Robustness of Contrast in /s/ and /ʃ/ productions based on Centroid frequency measurements: 1) within-category dispersion (average standard deviation in Centroid frequencies for each sound-category); 2) between category distance (difference between the mean Centroid frequencies of each category); 3) discriminability (between-category distance divided by the square root of the mean Centroid frequency variances for each category); and 4) percentage of tokens correctly classified by an individual regression slope, calculated from logistic regressions for each speaker (hereafter, %CP). Figure 1 shows how discriminability is affected by both between-category distance and within-category dispersion. The authors found that all four contrast measures were significantly correlated with age, and %CP, between-category distance, and discriminability were also correlated with receptive vocabulary. Among the four robustness measures, the authors found that %CP had the strongest correlation with naive listeners' ratings of perceived goodness. These results supported an earlier finding by Hazan and Baker (2011) which showed that cross-category distance and within-category dispersion was not well-correlated with fine-grained measures of speech perception. Further research is needed to explore how Robustness of

Contrast measures could be used to quantify speech-sound contrasts that are acquired earlier in the sequence of development, such as the /t/—k/ contrast.

The goal of the present study is to quantify the contrast between /t/ and /k/ productions. Two central measures—Centroid and Peak ERB—will be compared in terms of their utility in measuring the robustness of the /t/—k/ contrast in both adults and children.

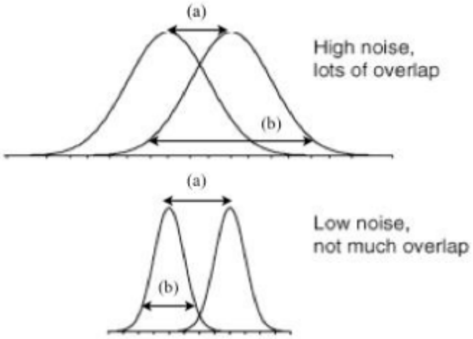


Figure 1.1. Effects of between-category distance and within-category dispersion on discriminability. Top graph shows poor discriminability due to low between-category distance (a) and high within-category dispersion (b). Bottom graph shows good discriminability due to high between-category distance (a) and low within-category dispersion (b).

CHAPTER TWO
Methods—Data Collection

2.1 Participants

Participants were recruited from greater Madison, WI and Minneapolis, MN communities through flyers, brochures, public events, and word of mouth. Adult participants included 10 females and 11 males (mean age: 20 years; range: 20-29 years). Child participants included 163 children (81 males and 82 females) who were part of a larger longitudinal project[1]. Thirteen of the children spoke African American English (AAE) as their native dialect (6 males and 7 females), and 150 children spoke Mainstream American English (MAE). Dialect status was inferred during the initial phone interview with the family and confirmed by an AAE-speaking examiner during the child's first visit to the lab. All participants were monolingual, native speakers of English with normal hearing and typical development. Parents reported no remarkable medical histories or enrollment in speech or language services. Descriptive statistics for the child participants are presented in Table 2.1 below. Some data are missing for certain children, because not all children completed every task (due to constraints on time, attention, or difficulty eliciting responses).

Table 2.1. Descriptive data for participants

Variable	**n**	**Mean (SD)**	**Range**
Age (months)	163	32.7 (3.4)	28-39
EVT-2 (standard score)	160	118.1 (15.2)	81 - 160
PPVT-4 (standard score)	157	115.2 (16.5)	79 - 153
GFTA-2 (standard score)[1]	146	94.4 (11.5)	70 - 119

[1] Twenty-two additional children were recorded but excluded from spectral analyses due to too few analyzable productions (4 correct productions in both front- and back-vowel contexts that were unobscured by noise).

Information about maternal education was collected from a background questionnaire for 162 of the participants. One parent chose not to complete the questionnaire. Descriptive data related to maternal education are presented in Table 2.2 below.

Table 2.2. Maternal education data

Education Level Reported	**n**
High School Diploma, GED, or Less than High School	13
Trade School, Technical/Associate's Degree, or Some College	24
College Degree	60
Graduate Degree	65
Total	162

2.2 Stimuli

Two adult females were recorded in a sound-treated room to create the experimental stimuli. One speaker produced the target words in Mainstream American English, and the other speaker produced them in African American English. Recordings were amplitude normalized. Each word was paired with an archetypal, high-quality photograph of the object. Images were obtained from online sources and edited for consistency in size and background. The entire experiment was programmed and presented using *Eprime*® 2.0.

There were 99 stimulus items in the experimental task. For the present study, a subset of 34 tokens were included in analyses. This subset contained 17 familiar words, 8 with initial /t/ and 9 with initial /k/ consonants. Target consonants were followed by a variety of vowels with

[1] For 71 of 146 participants, fewer than the total number of targets (77) could be transcribed because 1) the child did not produce all of the words; 2) there was background noise during a production; or 3) the experimenter spoke over the child. In these cases, the raw score was adjusted for the number of consonants/consonant clusters produced relative to the maximum number, and the standard score was calculated based on this adjusted raw score. The average number of words that could be transcribed overall was 76, only 5 children had fewer than 70 transcribable productions, and the lowest number of transcribable words in the sample was 62.

relatively even distribution across front- and back-vowel contexts. Each word was repeated once in order to obtain a reasonably large number of productions (n = 34) per child. Each repetition was paired with a novel image and a new auditory prompt to keep the task engaging. Words were selected if 1) they could be represented by an image, and 2) if at least 80% of 30-month old children understand and produce them (according to normative data from the *MacArther-Bates Communicative Development Inventory* (*CDI*; Fenson et al., 1993)). The /t/- and /k/-initial words included in the final corpus are presented below in Table 2.3.

Table 2.3. Stimuli: /t/- and /k/-initial words used in the experimental task

Target Consonant	**Orthographic Spelling**	**Phonetic Spelling**	**Vowel Context**
/t/	tickle	/tɪkl̩/	Front
/t/	table	/te͜ɪbl̩/	Front
/t/	tape	/te͜ɪp/	Front
/t/	teddy bear	/tɛdibe͜ɪɹ/	Front
/t/	tooth	/tuθ/	Back
/t/	toast	/to͜ʊst/	Back
/t/	tummy	/tʌmi/	Back
/t/	tongue	/tʌŋ/	Back
/k/	kitchen	/kɪt͜ʃɪn/	Front
/k/	kitty	/kɪɾi/	Front
/k/	cake	/ke͜ɪk/	Front
/k/	cat	/kæt/	Front
/k/	candy	/kændi/	Front
/k/	cookie	/kʊki/	Back
/k/	coat	/ko͜ʊt/	Back
/k/	cup	/kʌp/	Back
/k/	car	/kɑɹ/	Back

Total number of coronal tokens = 16 (8 in front vowel context)
Total number of dorsal tokens = 18 (10 in front vowel context)

2.3 Procedure

Children participated in a sound-treated lab setting with support from two or three trained research assistants at either the University of Wisconsin-Madison or the University of Minnesota-Twin Cities. Most children completed all experimental tasks within three, 2-hour visits, but some children needed one or two additional sessions to complete all tasks. Families were compensated monetarily for their participation at the end of each session. During their visits to the lab, children received a hearing screening and engaged in several other experimental tasks related to the larger longitudinal project. A visual schedule was used to keep the child on track and communicate progress throughout the visit. The child earned stickers for each completed task, a toy prize at the end of each session, and a book for completion of the study at each year. All experiments and standardized tests were presented in the child's native dialect.

During the experimental task, children sat in front of a computer screen, positioned approximately 4-6 inches away from a Shure SM81 cardioid condenser microphone with a custom pop filter. The microphone's built-in 18 dB/octave roll-off high-pass filter was used to reduce background noise below 60 Hz. Stimuli were presented auditorily through a speaker system and visually on the computer screen in a pseudo-randomized order across participants, with steps taken to ensure target words were not repeated on consecutive trials. Children repeated the words into the microphone, and an experimenter recorded the productions using a Marantz PMD671 solid-state recorder at a sampling frequency of 44,100 Hz. Digital recordings were saved for later analyses.

Four training trials preceded the experiment to familiarize the children with the task and behavioral expectations, as well as to attain appropriate recording levels. Training trials could be repeated as many times as necessary to satisfy these conditions. During the experimental phase, stimuli could be repeated up to three times if necessary to elicit an analyzable production. Repetitions were allowed if there was noise obscuring stimulus presentation, the child misidentified the target, or the child became distracted. Children usually produced the target word immediately following presentation of the stimulus, but sometimes additional prompting from the examiner was needed to elicit a response (e.g., “What did the computer say?” or “Now you say ‘kitty!’”). Examiners also prompted the child to repeat a production if the child whispered or shouted, or if there was noise obscuring the response (e.g., child touched the microphone, tapped the table, kicked the chair). Progress was communicated to the child throughout the task visually via an animal avatar of the child’s choice: every few productions, the avatar ascended one rung of a ladder pictured on the side of the screen, and the task was complete when the avatar reached the top.

CHAPTER THREE
Methods—Data Analysis

3.1 Coding

Each participant's recording was coded using *Praat*®. Coding occurred in a multi-stage process. First, trained research assistants listened to the audio recordings and marked the boundaries for each target word. They also noted the context of the participant's response (i.e., whether the production was in direct response to the computer stimulus, or whether the examiner prompted the child). If a child did not produce a target, this was coded as a non-response. Figure 3.1 shows an example of the Pratt window during the first stage of coding.

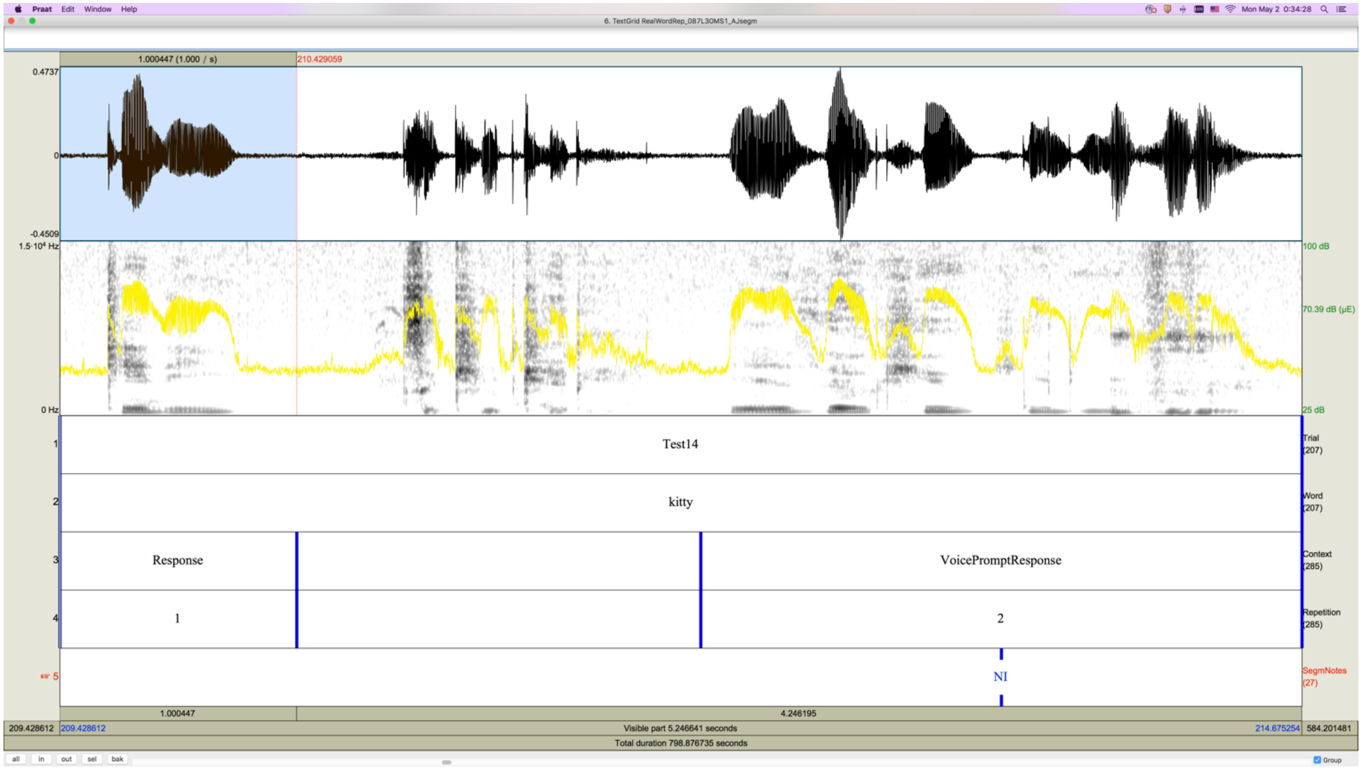
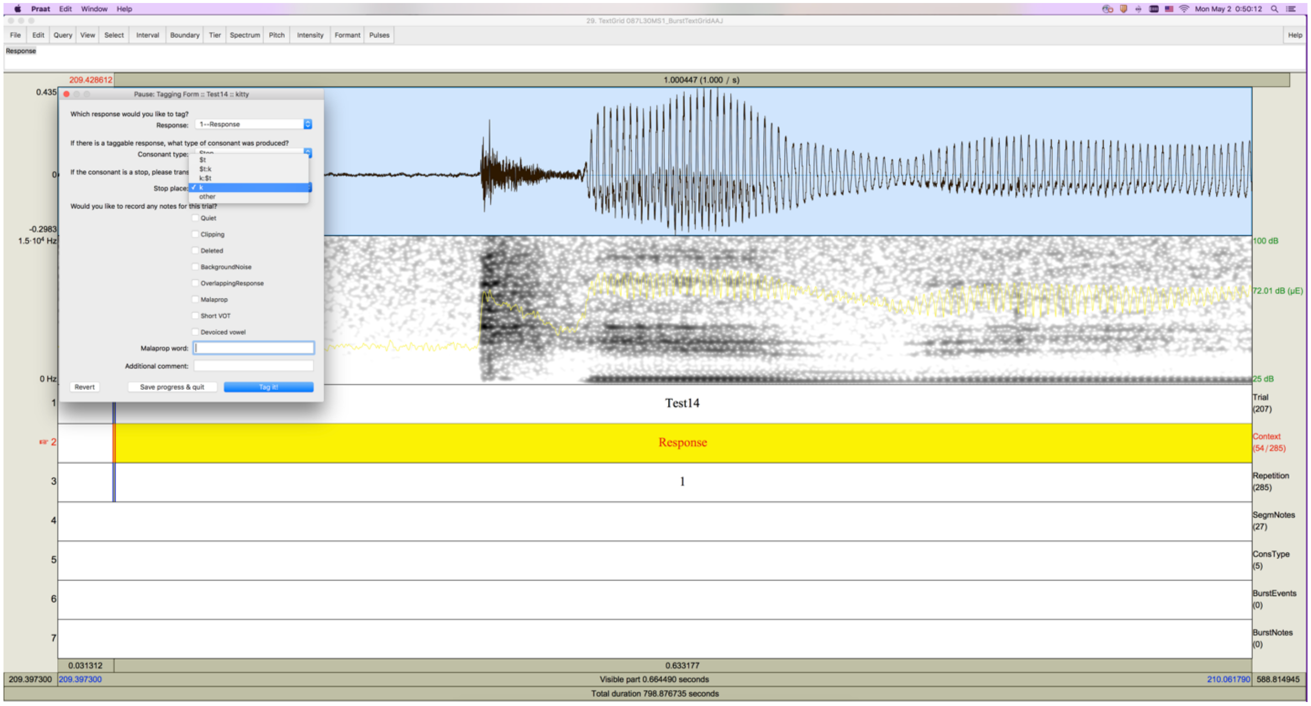


Figure 3.1. Stage 1 of coding. In this example, the child produced the target word "kitty" twice: the first "Response" was a repetition immediately following the stimulus, and the second "VoicePromptResponse" was in response to the examiner's prompt (i.e., Child: "Kitty." Examiner: "Will you say kitty again?" Child: "I have that kitty at home.") The "NI" denotes the target consonant was not produced phrase-initially.

Next, a research assistant with experience in phonetic transcription and acoustic phonetics made a binary choice of whether the production was a stop or not (Stage 2 of coding). If the production were a stop, the transcriber made a relatively narrow decision about place-of-articulation (Stage 3 of coding). These transcriptions included [t] and [k], intermediate categories (i.e., [t:k] if the production were perceptually intermediate, but closer to [t]; [k:t], if the production were intermediate but closer to [k]) and "other" for bilabial productions. This level of transcription also included a '$' symbol if the production was a substitution (e.g., if a child produced "tat" for *cat*, the initial consonant would be transcribed as [$t]). Notes could also be added at this stage, such as the recording clipped, production of the target overlapped with stimulus presentation, or background noise obscured the response. The first usable response was always chosen if there were multiple productions of a word. "Useable" was defined as a response unobscured by background noise and without clipping in the recording. If the child self-corrected a production, the corrected production was transcribed. Figure 3.2 shows an example of the Praat window during this stage of coding.



Pause: Tagging Form :: Test14 :: kitty

Which response would you like to tag?
Response: 1--Response

If there is a taggable response, what type of consonant was produced?
Consonant type: Stop

If the consonant is a stop, please trans
Stop place: $t / $t:k / k:$t / ✓ k / other

Would you like to record any notes for this trial?
□ Quiet
□ Clipping
□ Deleted
□ BackgroundNoise
□ OverlappingResponse
□ Malaprop
□ Short VOT
□ Devoiced vowel

Malaprop word:
Additional comment:

Figure 3.2. Stages 2 and 3 of coding. The first response was deemed useable, the manner of articulation for this target consonant was judged to be “stop”, and the production was transcribed as a correct [k].

Finally, for all productions transcribed as stops, the release-burst and the onset of voicing were marked in Stage 4 of coding. The onset of voicing was defined as the first upswing from the zero crossing on the waveform followed by a stable, quasi-periodic pattern of voicing. The release-burst was defined as a transient-noise spike following a period of silence that corresponded perceptually to the release of a lingual constriction. If multiple burst phenomena were observed, additional steps were taken. First, the intensity (in dB) of each burst was measured, as well as the time (in ms) between them. If the two bursts were within 20ms and within 15dB of each other, the first burst was tagged. If the two bursts were within 15dB of each other but greater than 20ms apart, the second burst was tagged. If the bursts differed by 15dB or more, the burst with greater intensity was marked. Figure 3.3 shows an example of the Praat window during Stage 4 of coding.

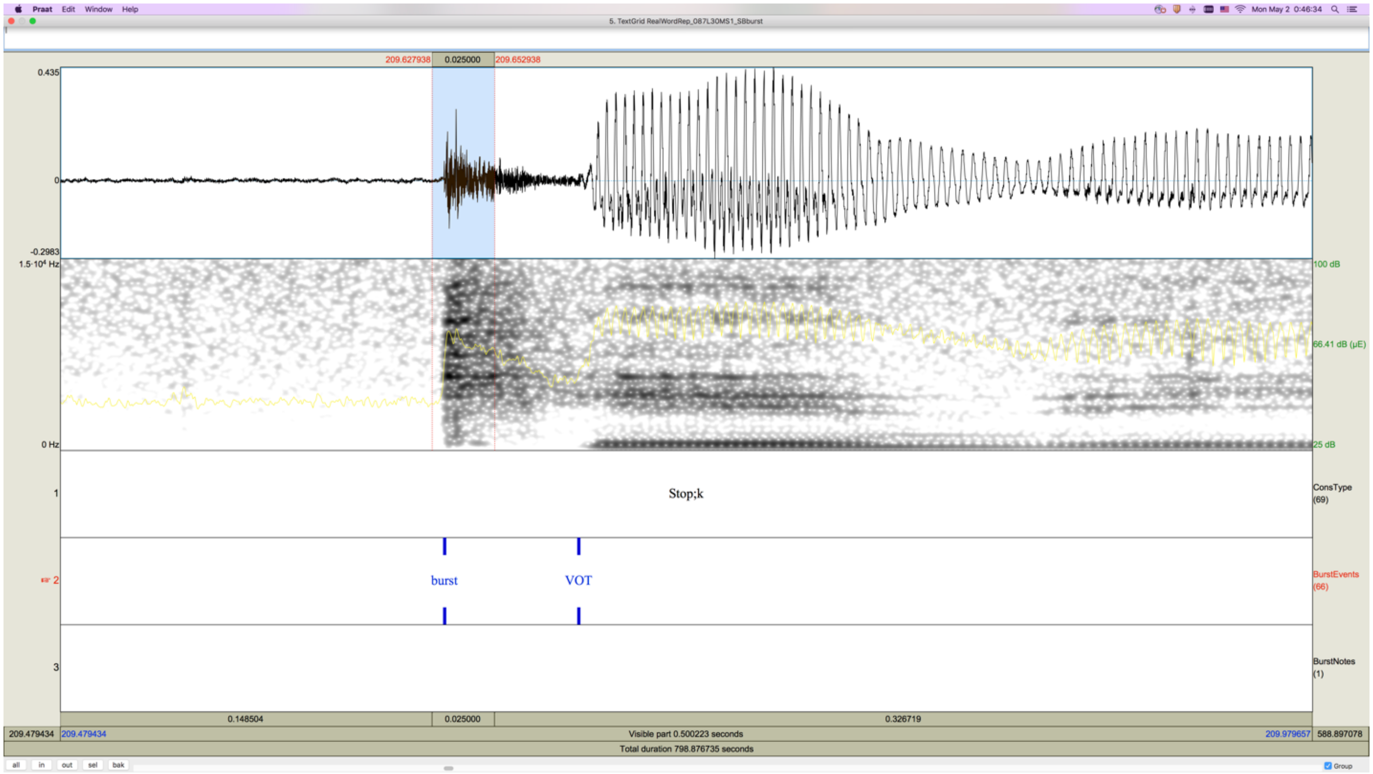


Figure 3.3. Stage 4 of coding. The release burst and VOT were marked using information present in the waveform and spectrogram. The highlighted portion shows 5ms prior to the burst's onset through 20ms.

3.2 Inter-rater Reliability

An ongoing calibration and consensus process was used during the transcription and tagging stages. Each research assistant kept track of difficult or ambiguous cases while tagging, and then met with the other taggers to gain input and reach a consensus. Additionally, 20% of the files will be tagged by two or more assistants to compute traditional inter-rater reliability. A simulation will also be performed to determine whether the results of statistical analyses are influenced by various taggers.

3.3 Spectral Analyses

Summary acoustic measures were obtained using RStudio©. For the spectral analyses, analyzable tokens included productions that: 1) were transcribed as lingual stops with coronal, dorsal, or intermediate place-of-articulation; 2) had voice-onset-time (VOT) greater than 20ms; and 3) had release-bursts unobscured by background noise. Participants were excluded from the analysis if they did not produce at least 4 analyzable tokens in both front- and back- vowel contexts. For each analyzable production, 5ms preceding the burst through 20ms following the burst was extracted with a rectangular analysis window from the source file. Figure 3.3 shows an example of the 25ms window that was extracted from the .wav file. The spectrum of the window was estimated with zero-padding, using a multitier spectrum with parameters K= 8, NW = 4. Due to a relatively intense, low-frequency noise floor, the children's recordings were also high-pass filtered with a first-order FIR filter.

The summary acoustic measure for each production—Centroid frequency—was computed from each spectrum on a linear scale ranging from 926.4 Hz to 15,178.7 Hz. The values of the spectrum within this range were normalized, so the total power within the spectrum summed to 1. The Centroid frequency of the spectrum was computed as the sum of frequencies within this interval weighted by the normalized spectral power at each frequency. In analogous terms, the normalized spectrum was treated as a discrete probability mass function over frequency, and the Centroid frequency was computed as the expected frequency value of the distribution.

The summary psychoacoustic measure for each production—Peak ERB—was calculated by passing the estimated spectrum through a bank of bandpass filters. Each filter in the bank was a 4th-order gammatone filter whose bandwidth was proportional to its center frequency. Variable bandwidths were used because the auditory filters are wider at high frequencies compared to low frequencies. The center frequencies of the gammatone filters were spaced 0.1 ERB apart along the ERB-number scale ranging from 15 to 39 (equivalent to the acoustic range used when calculating Centroid, i.e., 15 ERB = 926.4 Hz, and 39 ERB = 15,178.7 Hz). The evenly spaced filters along the psychoacoustic scale modeled the fact that the auditory periphery logarithmically compresses the physical Hz frequency scale. The output of each channel in the filter bank was summed, and each channel's total power was plotted against that channel's center frequency on the ERB-scale, yielding a 'psychoacoustic spectrum' or 'excitation pattern.' Peak ERB was the frequency component of the psychoacoustic spectrum with the greatest amplitude.

3.4 Statistical Analyses

Several steps were taken to prepare the data for statistical analysis. First, separate datasets were created for the adults' productions and the children's productions, and all analyses were performed separately for children and adults. For accuracy measures, each lingual stop production that was transcribed with correct place-of-articulation and had VOT >20ms was assigned a 1 for Accuracy, and each production that was transcribed as incorrect (including VOT <20ms) was assigned a 0 for Accuracy. Intermediate productions that were transcribed as closer to the target were coded as correct. To be included in the subsequent analyses, tokens had to be transcribed as correct (i.e., assigned a 1), and analyzable (not obscured by noise). For spectral measures, Centroid measurements were converted into kHz, so the values were more similar in range to the Peak ERB measures. Finally, Centroid in kHz and Peak ERB were both mean-centered in order to increase the likelihood that statistical models would converge and improve interpretability of the model's parameter estimates.

Four separate mixed-effects logistic regression models were used to analyze each dataset (again, separate analyses were done for children and adults). The first model included Centroid (kHz) as the central measure, and the second model included Peak (ERB) as the central measure. Both models predicted the likelihood that target consonant was /t/ or /k/ based on: fixed effects of central measure, vowel context, and their interaction; and random effects of the intercept and slope for central measure by-participant. Random effects were allowed to be correlated. The models were constructed for the RStudio© package *lme4*, version 1.1-11 (Bates, Maechler, Bolker, & Walker), as follows:

Model 1: glmer(Target Consonant ~ Centroid.kHz.c * Vowel Context + (1 + Centroid.kHz.c | ID))

Model 2: glmer(Target Consonant ~ PeakERB.c * Vowel Context + (1 + PeakERB.c | ID))

From the output of Models 1 and 2, the probability that each production's target consonant was /t/ were calculated. If the probability was greater than 50%, the model predicted the target consonant was /t/. If the probability was less than 50%, the model predicted the target consonant was /k/. If the predicted target consonant matched the actual target consonant (i.e., the model made a correct prediction), the token was assigned a 1 for Predicted Accuracy. If the model mis-classified the consonant (the model's prediction was incorrect), the token was assigned a 0 for Predicted Accuracy.

The third and fourth mixed-effects logistic regression models were used to determine which central measure (Centroid or Peak ERB) better differentiated /t/ and /k/. This was defined as a significantly higher log likelihood that predictions were made accurately by Model 1 (Centroid model) or Model 2 (Peak ERB model). Model 3 was built on productions in front-vowel contexts, and Model 4 was built on productions in back-vowel contexts. Both models included Predicted Accuracy (assignment of 1 or 0 from results of the first two models) as the outcome variable, with a fixed effect of group (group 1 was Centroid, group 2 was Peak ERB), and a random intercept by-participant. These models were constructed as follows:

Models 3 & 4: glmer(Predicted Accuracy ~ Central Measure + (1 | ID), family = 'binomial')

The results of Models 3 and 4 directly address the research question of this study: is Centroid or Peak ERB a better central measure for differentiating /t/ and /k/ productions.

CHAPTER FOUR
Results

4.1 Adults—Accuracy based on transcription

Based on transcriptions, adults produced /t/ and /k/ targets with 99.8% accuracy. One adult produced a single [k] token with VOT < 20ms, decreasing the expected 100% accuracy value. A total of 657 productions across 21 adults were analyzable (correctly produced and unobscured by noise) and included in the subsequent spectral analyses (mean: 31 productions per adult).

4.2 Adults—Differentiating /t/ and /k/

For the adults, Model 1—using Centroid to predict Target consonant—made accurate predictions 95% of the time (94% accurate for target /t/, and 96% accurate for target /k/). Model 2—using Peak ERB to predict Target consonant—made accurate predictions 92% of the time (88% accurate for target /t/, and 95% accurate for target /k/). Table 4.1 shows accuracy of the models' predictions for target /t/ and target /k/ productions separate for front- and back-vowel contexts.

Table 4.1. Mean accuracy of the predictions made by Model 1 and Model 2 for adults

	Target /t/		**Target /k/**	
Centroid (Model 1)	**Front** 92%	**Back** 98%	**Front** 95%	**Back** 96%
Peak ERB (Model 2)	**Front** 85%	**Back** 92%	**Front** 98%	**Back** 93%

Then, Model 3 and Model 4 were used to compare the prediction accuracy of the two central measures in front- and back-vowel contexts, respectively.

Model 3 compared the prediction accuracy of Centroid vs. Peak ERB for correct productions in front-vowel contexts (i.e., evaluated whether Model 1 or Model 2 made more accurate predictions in front-vowel contexts). Model 3 did not show a significant effect of central measure ($\hat{\beta} = -0.37$, $SE = 0.31$, $z = -1.21$, $p = 0.23$), although there was a slight, non-significant trend toward lower predicted accuracy when Peak ERB was the central measure. These results suggest that for adults' productions in front vowel contexts, both central measures were equally successful in differentiating /t/ and /k/. The left side of Figure 4.1 (below) shows the results of Model 3.

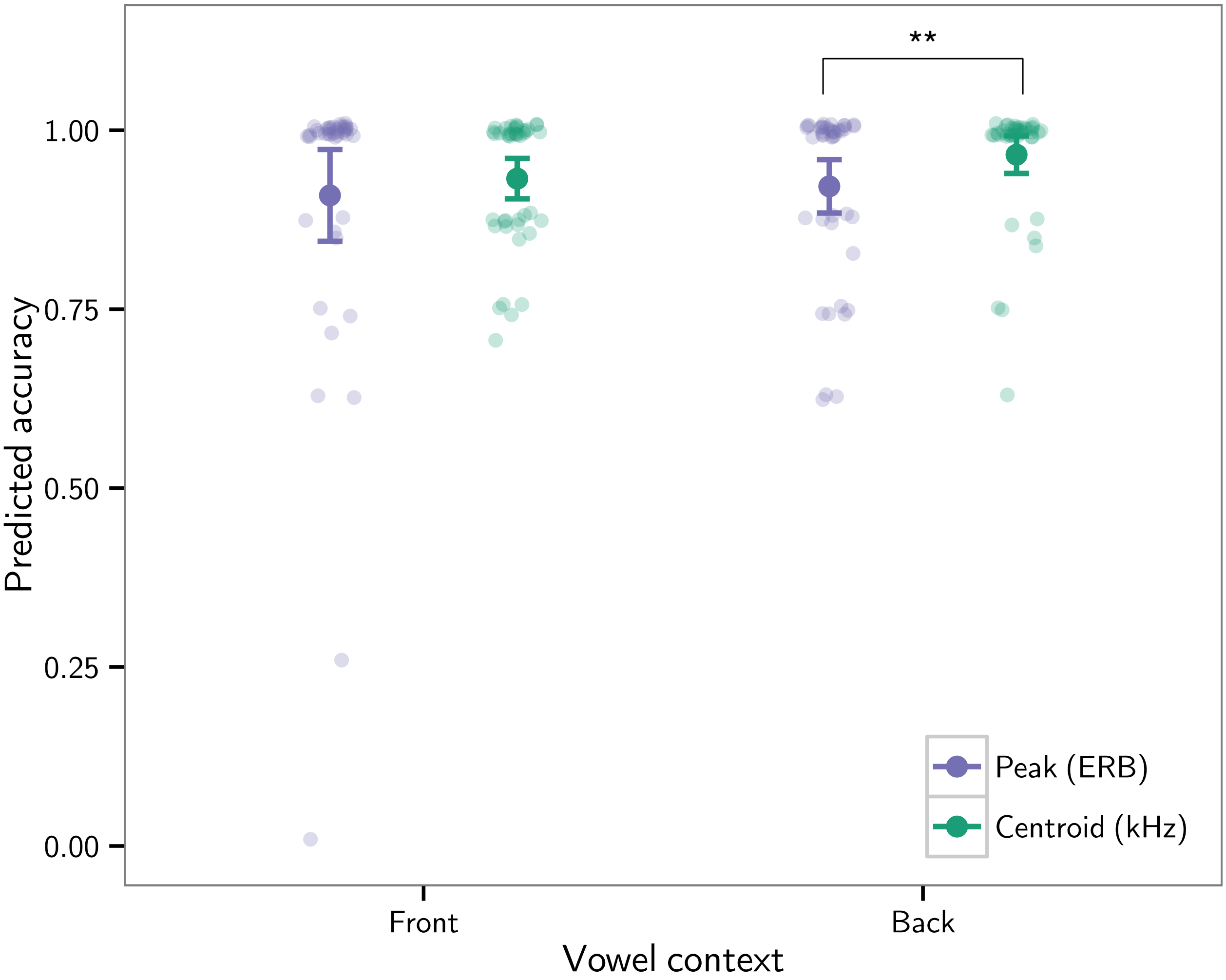


Figure 4.1. Predicted accuracy by central measure, separated for tokens in front- and back-vowel contexts for adults.

Model 4 compared the prediction accuracy of Centroid vs. Peak ERB for correct productions in back-vowel contexts (i.e., evaluated whether Model 1 or Model 2 made more accurate predictions in back-vowel contexts). Model 4 showed a significant effect of central measure: in back-vowel contexts, predicted accuracy was significantly lower when Peak ERB was the central measure ($\hat{\beta}$ = -1.01, *SE* = 0.39, *z* = -2.61, *p* = 0.009). These results suggest that for adults' productions in back-vowel contexts, Centroid was a better central measure for differentiating /t/ and /k/. The right side of Figure 4.1 (above) shows the significant results of Model 4.

4.3 Children—Accuracy based on transcription

For the 185 children who participated in the experimental task, /t/ and /k/ targets were produced with 74.7% accuracy. Of these children, 22 were excluded from spectral analyses due to too few analyzable tokens. To be included, at least four tokens in each vowel context had to be produced correctly and unobscured by noise. For the remaining 163 children, overall accuracy of /t/ and /k/ productions was 81.3%.

For the 163 children included in spectral analyses, /t/ targets were produced slightly more accurately (83%) than /k/ targets (80%). Productions of /t/ targets in front-vowel contexts were produced slightly less accurately (81%) than productions of /t/ in back-vowel contexts (85%). Productions of /k/ targets followed a similar trend: 77% accuracy in front-vowel contexts, 83% accuracy in back-vowel contexts. A total of 4,193 productions were included in spectral analyses (mean: 26 per child).

4.4 Children—Differentiating /t/ and /k/

Model 1—using Centroid to predict Target consonant—made accurate predictions 79% of the time (69% accurate for target /t/, and 81% accurate for target /k/). Model 2—using Peak ERB to predict Target consonant—made accurate predictions 72% of the time (58% accurate for target /t/, and 79% accurate for target /k/). Table 4.2 shows the mean accuracy of the models' predictions for target /t/ and target /k/ separately for front- and back-vowel contexts.

Table 4.2. Mean accuracy of the predictions made by Model 1 and Model 2 for children

	Target /t/		**Target /k/**	
Centroid (Model 1)	**Front** 54%	**Back** 85%	**Front** 78%	**Back** 85%
Peak ERB (Model 2)	**Front** 44%	**Back** 71%	**Front** 86%	**Back** 72%

Figure 4.2 shows the results of Model 1 for a single child, and Figure 4.3 shows the results of Model 2 for that same child. Raw data are plotted as circles: productions transcribed as [k] are on the bottom of the figures and productions transcribed as [t] are at the top; productions in front-vowel context are in blue, and productions in back-vowel context are in orange. Blue and orange lines represent the model's predictions for tokens in front- and back-vowel contexts, respectively. A dashed, vertical, decision boundary line is drawn where the probability that a production was a /t/ equals 50%. For [t] tokens at the top of the figures, anything to the left of these decision boundaries was mis-classified by the model (i.e., the model incorrectly classified the production as a [k]). For [k] tokens on the bottom of the figures, anything to the right of the decision boundaries was mis-classified by the model (i.e., the model incorrectly classified the production as a [t]).

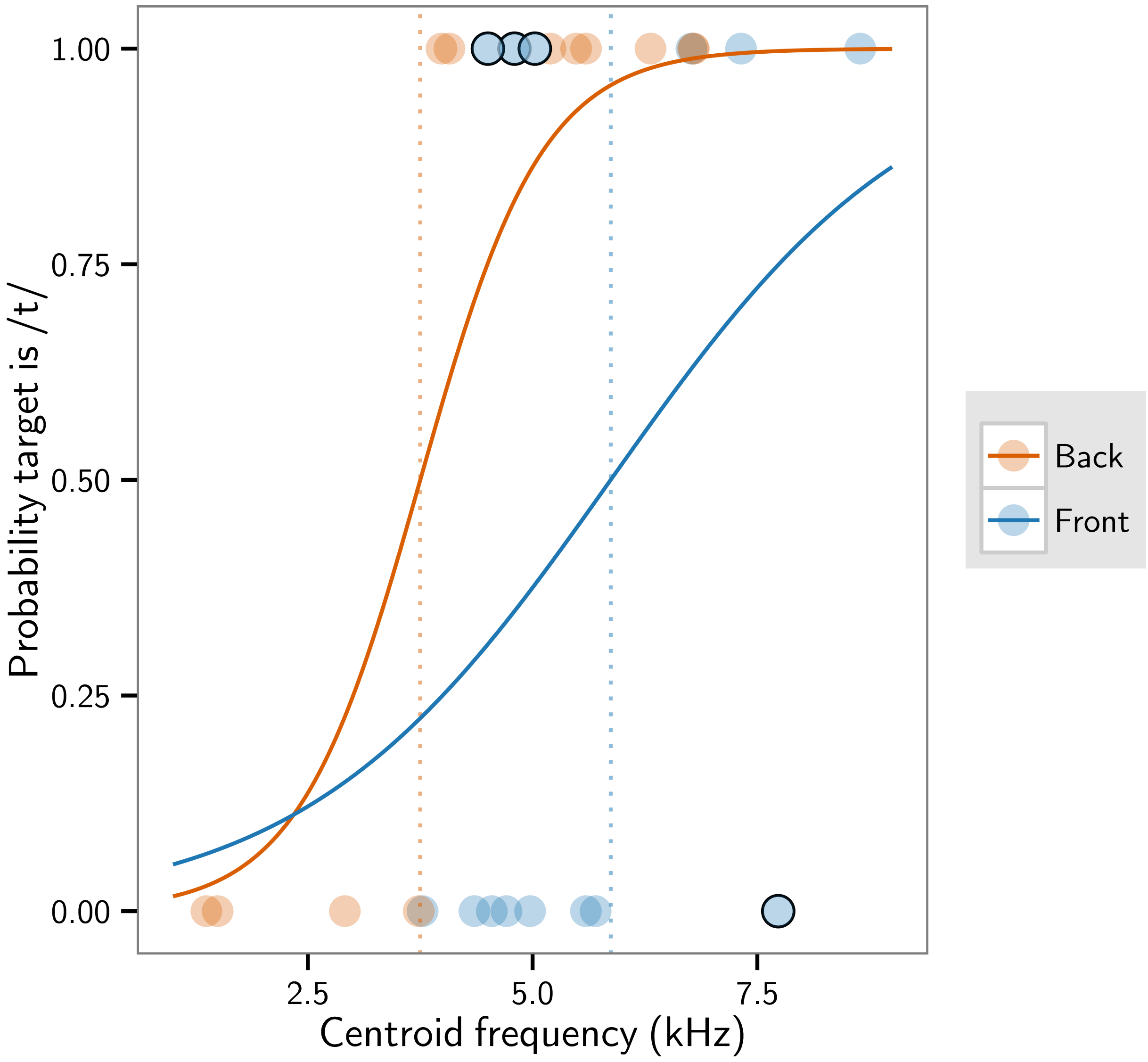


Figure 4.2. Results of Model 1: Predicting target consonant from Centroid measurements. This figure shows the classification accuracy of Model 1 for a single male participant. Raw data are plotted as circles, with [t] tokens at the top of the figure and [k] tokens at the bottom. Data in orange are tokens in back-vowel contexts, and data in blue are tokens in front-vowel contexts. Model prediction lines are shown for each phonological context, with a vertical line representing the 50% probability decision boundary. Raw data encircled in black are those that were misclassified by the model. For this child, the model made accurate predictions 85% of the time: three [t] productions were classified as [k], and one [k] production was classified as [t].

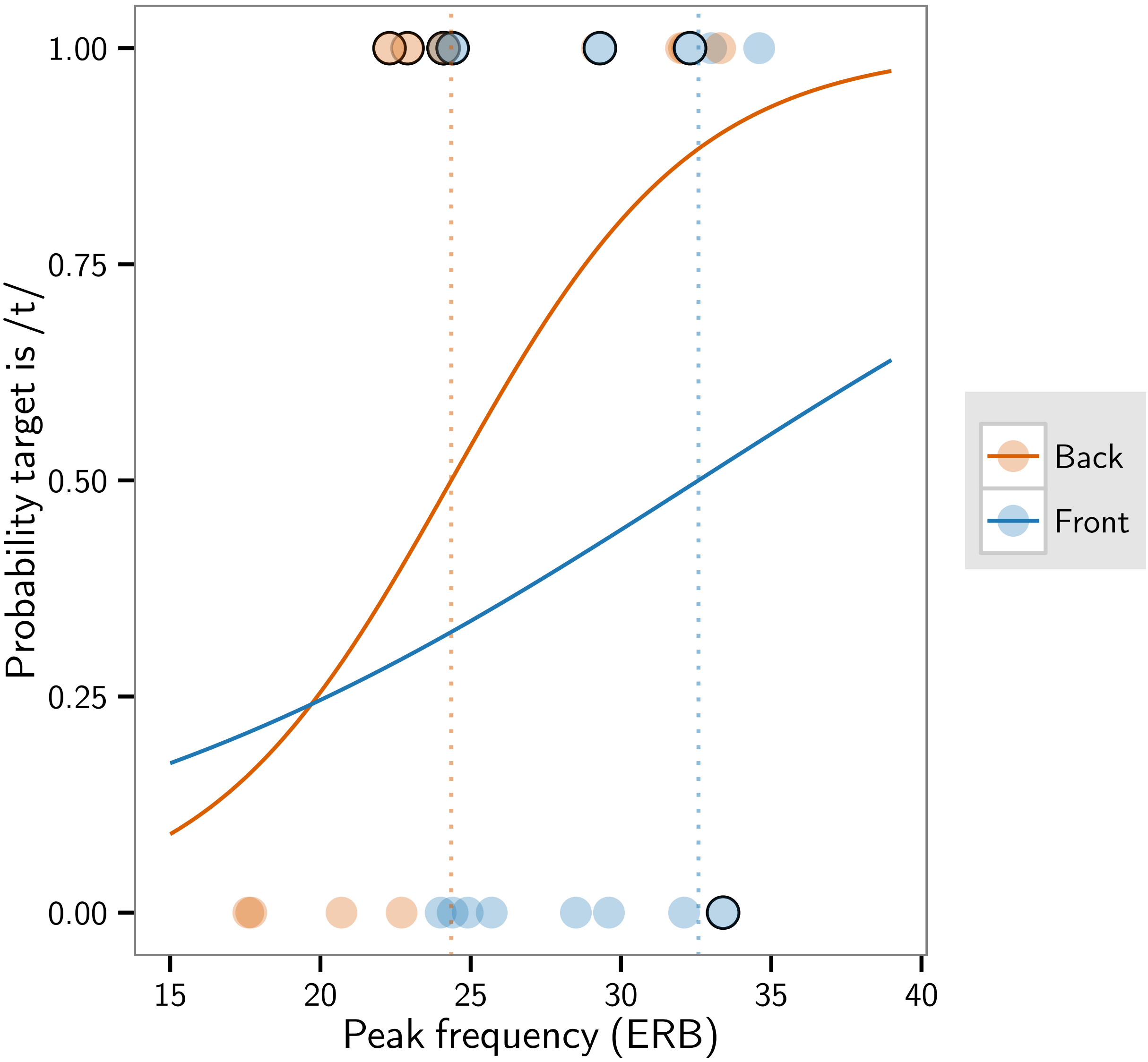


Figure 4.3. Results of Model 2: Predicting target consonant from ERB measurements. This figure shows the classification accuracy of Model 2 for a single male participant. Raw data are plotted as circles, with [t] tokens at the top of the figure and [k] tokens at the bottom. Data in orange are tokens in back-vowel contexts, and data in blue are tokens in front-vowel contexts. Model prediction lines are shown for each phonological context, with a vertical line representing the 50% probability decision boundary. Raw data encircled in black are those that were misclassified by the model. For this child, the model made accurate predictions 69% of the time: six [t] productions were classified as [k], and one [k] production was classified as [t].

Again, Models 3 and 4 were used to compare the prediction accuracy of the two summary central measures in front- and back-vowel contexts, respectively.

Model 3 compared the prediction accuracy of Centroid vs. Peak ERB for correct productions in front-vowel contexts (i.e., evaluated whether Model 1 or Model 2 made more accurate predictions in front-vowel contexts). Model 3 did not show a significant effect of central measure on predicted accuracy ($\hat{\beta}$ = -0.04, *SE* = 0.07, *z* = -0.61, *p* = 0.54), although there was a slight, non-significant trend toward lower predicted accuracy when Peak ERB was the central measure. These results suggest that for children's productions in front-vowel contexts, both central measures were comparable in differentiating /t/ and /k/. The left side of Figure 4.4 shows the results of Model 3.

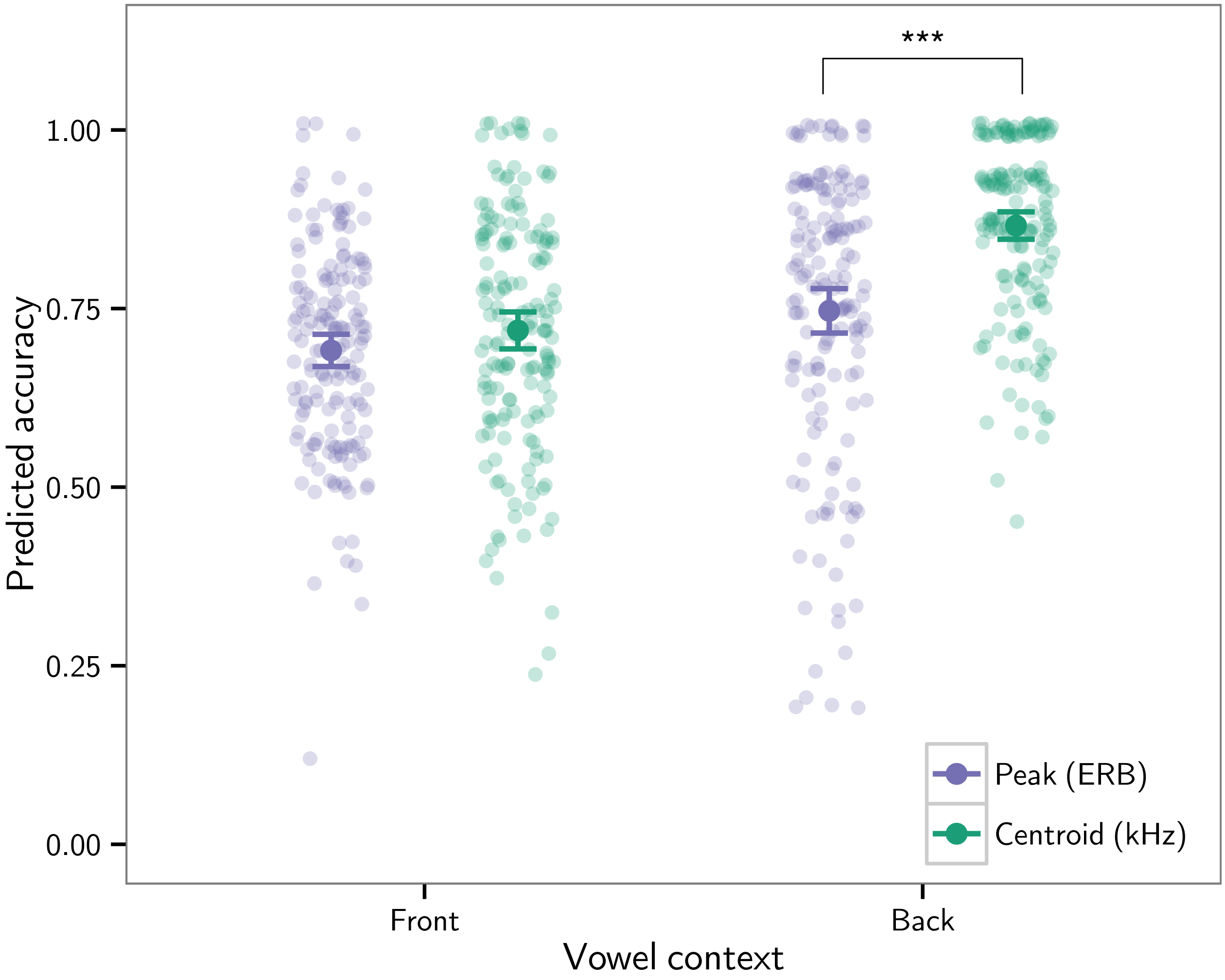


Figure 4.4. Predicted accuracy by central measure, separated for tokens in front- and back-vowel contexts for children.

Model 4 compared the prediction accuracy of Centroid vs. Peak ERB for correct productions in back-vowel contexts (i.e., evaluated whether Model 1 or Model 2 made more accurate predictions in back-vowel contexts). Model 4 showed a significant effect of central measure: in back-vowel contexts, predicted accuracy was significantly lower when Peak ERB was the central measure ($\hat{\beta}$ = -0.92, *SE* = 0.08, *z* = -10.87, *p* < 0.001). These results suggest that for children's productions in back-vowel contexts, Centroid was a better measure for differentiating /t/ and /k/. The right side of Figure 4.4 shows the significant results of Model 4.

Additional models were fit for the children to evaluate a possible effect of target consonant on predicted accuracy. Separate models were fit for front- and back-vowel contexts (Models 5 and 6, respectively). These models included a main effect of target consonant and an interaction between central measure and target consonant. The resulting models were structured as follows:

Models 5 & 6: Predicted Accuracy ~ Central Measure * Target Consonant + (1 | ID)

For correct productions in front-vowel contexts, Model 5 showed significant main effects of central measure ($\hat{\beta}$ = 0.48, *SE* = 0.12, *z* = -3.93, *p* < 0.001) and target consonant ($\hat{\beta}$ = -1.5, *SE* = 0.11, *z* = -14.57, *p* <0.001), as well as a significant interaction ($\hat{\beta}$ = -0.85, *SE* = 0.16, *z* = -5.51, *p* <0.001). These results indicate that in front-vowel contexts, productions with target /t/ were predicted less accurately than productions with target /k/. The significant interaction indicates that target /t/ productions were predicted more accurately when Centroid was used, but target /k/ productions were predicted more accurately when Peak ERB was used. These results are shown in the left panel of Figure 4.5.

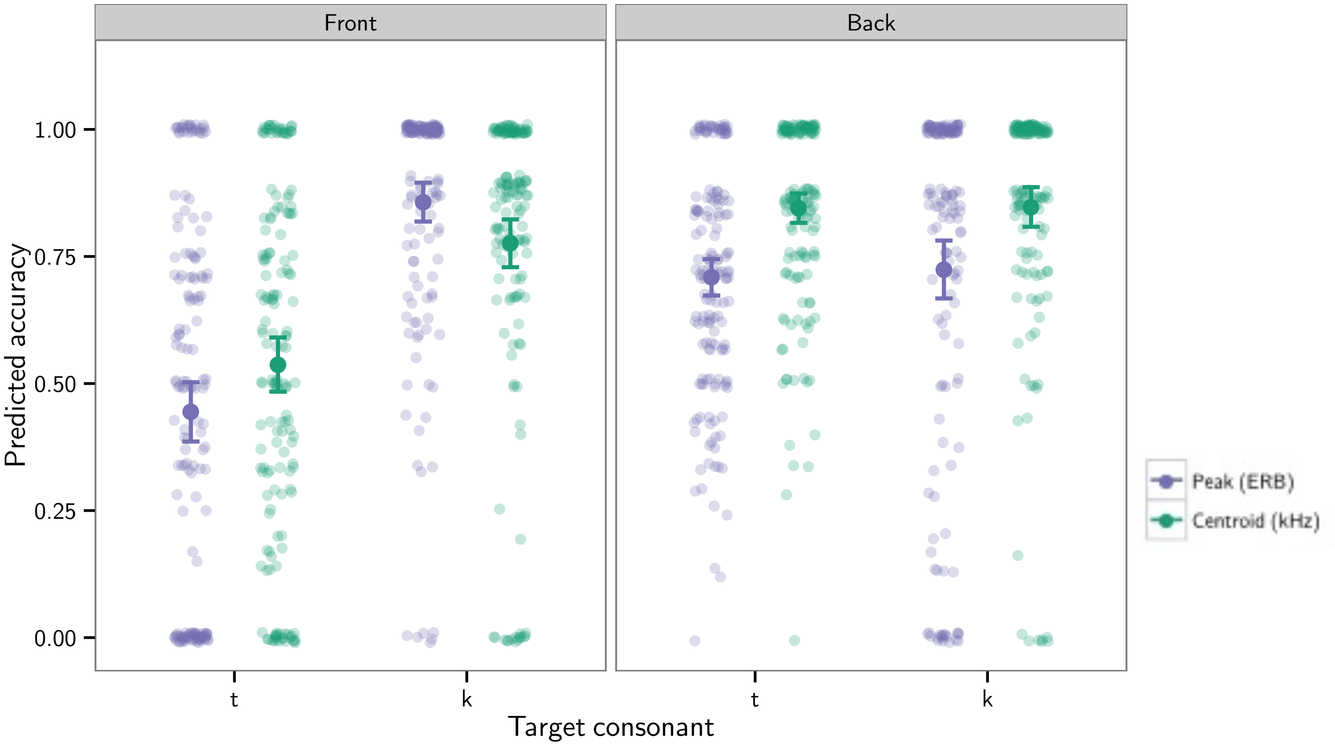


Figure 4.5. Predicted accuracy by central measure, separated by vowel context and target consonant for children.

For correct productions in back vowel contexts, Model 6 showed significant main effects of central measure ($\hat{\beta}$ = -0.91, *SE* = 0.13, *z* = -7.25, *p* < 0.001) and target consonant ($\hat{\beta}$ = -0.33, *SE* = .13, *z* = -2.47, *p* <0.001), but the interaction was not significant ($\hat{\beta}$ = -0.02, *SE* = 0.17, *z* = -0.13, *p* = 0.9). These results suggest that in back vowel contexts, productions with target /t/ were predicted less accurately than productions with target /k/, and overall, Centroid was significantly better at differentiating /t/ and /k/. These results are shown in the right panel of Figure 4.5.

CHAPTER FIVE
Discussion

The goal of the present study was to compare the utility of two central measures—Centroid and Peak ERB—in quantifying the robustness of contrast between word-initial [t] and [k] productions in both adults and children. Using an objective, gradient acoustic measure to supplement subjective, binary transcription decisions may present a more valid way to characterize subtle differences in speech productions, especially for children in the process of acquiring a particular contrast.

Twenty-one adults produced /t/ and /k/ words at ceiling-level accuracy, and both central measures were highly successful in predicting whether the target consonant was /t/ or /k/. While controlling for vowel context, the model predicting target consonant based on Centroid was accurate 95% of the time, and the model predicting target consonant based on Peak ERB was accurate 92% of the time. When comparing central measures directly, there was no difference between the two measures in front-vowel contexts, but Centroid better differentiated /t/ and /k/ in back-vowel contexts.

One hundred and sixty-three children produced /t/ and /k/ words with 81% accuracy (/t/ targets were produced slightly more accurately than /k/ targets, as expected for this age range). Compared to adults, both central measures were less successful in predicting whether the target consonant was /t/ or /k/, suggesting that children's productions exhibit less acoustic contrast overall. While controlling for vowel context, the model predicting target consonant based on Centroid was accurate 79% of the time, and the model predicting target consonant based on Peak ERB was accurate 72% of the time. When comparing central measures, results were similar to those for adults: there was no difference between the measures' accuracy in front vowel contexts, but Centroid better differentiated /t/ and /k/ in back-vowel contexts.

The finding for Centroid better differentiating /t/ and /k/ in back-vowel contexts could be related to the fact that Centroid is a more global measure compared to Peak ERB, so slight variations in amplitude of individual frequency components are less influential on the Centroid measurement, whereas variations in local peaks are likely to influence computation of Peak ERB.

For the children, there was also a significant interaction effect of target consonant, such that in front-vowel contexts, the Peak ERB model was more accurate than the Centroid model when the target consonant was /k/. There was also a significant main effect of target consonant, such that productions of target /t/ were predicted less accurately overall that productions of target /k/. These findings may be related to the shape of the spectral peaks for /t/ and /k/: perhaps because /t/ has a more diffuse spectral peak, it is more difficult to characterize using a single central measure, whereas /k/ has more distinct spectral peaks, and therefore could be better summarized using a single central measure. Furthermore, /k/'s distinctive peaks may be better classified by the local measure—Peak ERB—rather than the global Centroid measure when /k/ is fronted.

These results indicate that children produce a less robust acoustic contrast for /t/—/k/ than adults, even when only correct productions were included. These results also suggest that regardless of central measure, differentiating /t/ and /k/ in front vowel contexts is more difficult than differentiating /t/ and /k/ in back vowel contexts. This is likely due to unique spectral properties of /k/ in front-vowel contexts: when /k/ is produced in front-vowel contexts, the frequency components are higher, and therefore more similar to the frequency components found in /t/ productions. Thus, the model will be less successful differentiating /t/ and /k/ when /k/ is fronted by anticipatory coarticulation.

Limitations of this study should be discussed. First, there was an unexpected noise floor in the children's recordings. An intense, low-frequency noise was present throughout recordings, which created a necessity to pass the children's recordings through a high-pass filter. This additional manipulation of the acoustic signal was neither planned nor desirable, and may have had unexpected effects on central measurements. To avoid this issue in the future, it is recommended that the highest quality recording equipment be used in a sound-treated space, and noise floor measurements should not exceed 20dB.

Second, many tokens were excluded from analysis due to background noise during the response or the response overlapping with the stimulus. To increase the amount of useable data, it is recommended that a cue be built into the experiment so that children know exactly when they should start their responses. Also, experimenters may need extra support to determine whether responses began while the stimulus was still playing. One idea is to implement use of a software system that would produce a waveform in real time, so examiners could ensure there was time between stimulus offset and response onset.

There are many future directions given the current findings for this line of research. The next step will be to look at how the models classify all productions of lingual stops, including not only correct productions, but clear substitutions and intermediate productions transcribed as closer to incorrect. The current study only analyzed robustness of overt contrasts, and this future analysis could provide insight into children's productions of covert contrasts. Perhaps two children who consistently made [t/ for /k/ substitutions will have different degrees of robustness of contrast (i.e., the model makes more accurate predictions for one child compared to the other), suggesting that one child may be producing a covert contrast.

Another future analysis will include comparing each child's acoustic robustness of contrast with perceptual robustness of contrast. Perceptual robustness of contrast will be obtained by using a visual analog scale (VAS) rating to quantify robustness of contrast, as in Bernstein (2015), Kim (2016), and Holliday et al. (2015). Naïve listeners will hear /t/ and /k/ productions (including correct, incorrect, and intermediate productions) and rate them on a linear scale from 0 (very /t/-like) to 1 (very /k/-like). It's possible that even though Peak ERB was comparable to Centroid in differentiating /t/ and /k/ in front-vowel contexts and less accurate in back-vowel contexts, Peak ERB may be more related to gradient perceptual judgments, as it was designed to better reflect the human auditory system.

A possible path to further explore the current data and improve the models' abilities to differentiate /t/ and /k/ may involve incorporating additional spectral moments to improve classification accuracy. Because /t/ has a more diffuse spectral peak compared to /k/, additional measures of variance, skewness, and especially peakedness may facilitate the model's ability to differentiate /t/ and /k/ productions across phonological contexts. This could be especially relevant for quantifying robustness of the /t/—k/ contrast in children. Although a single central measure was overall highly accurate in classifying adults' productions, the children's smaller vocal tracts reduce the range of relevant frequencies, likely causing more overlap and less distance between centroid frequencies in /t/ and /k/ productions. An additional measure to describe the peakedness of the spectrum might serve in differentiating /t/ and /k/ productions in front-vowel contexts for children.

Another possible method to better characterize the stops would be to use a dynamic measure rather than static information within a single spectral slice. Analyzing the spectrum during the release-burst and its transition into the following vowel could provide additional cues and improve categorization accuracy in various phonological contexts (for examples, see Kewley-Port, Pisoni, & Studdert-Kennedy, (1983); Lahiri, Gewirth, & Blumstein, 1984; Nossair & Zahorian, 1991; Suomi, 1985; Walley & Carrell, 1983).

Finally, as the measurements collected from the children in this study were part of a larger longitudinal project, there are several avenues for individual differences research to determine which child-level factors, if any, predict early development of a robust contrast between /t/ and /k/. Vocabulary skills, speech perception skills, or articulation abilities overall may influence a child's ability to produce a clear contrast. Family factors could also play a role, such as maternal education, quantity and quality of language input in the home, the average number of conversational turns a child takes on a typical day, or how often the child participates in shared reading time with others. With the longitudinal data collected over several years, it would also be possible to look at a child's /t/—k/ contrast over time, and determine whether any child-level factors at 2-3-years of age predict more rapid growth.

To summarize, the present study explored two central measures—Centroid and Peak ERB—and their utility in quantifying robustness of the /t/—k/ contrast across various phonological contexts in children and adults. For both groups of speakers, Centroid and Peak ERB were comparable in differentiating /t/ and /k/ in front vowel contexts, but Centroid was significantly better in back vowel contexts. Children overall produced less robust contrasts compared to adults, even when only correct productions were analyzed, and this was especially true in front-vowel contexts, likely because /k/ becomes fronted and has spectral properties more similar to /t/.

However, when the target consonant was /k/, Peak ERB was better for differentiating the consonants, which could suggest that local peaks are more meaningful than a global average when /k/ becomes fronted.

The results of this study highlight the importance of using an objective, gradient measures to supplement transcription: even when all the /t/ and /k/ productions were transcribed as correct, there was a wide range in robustness of acoustic contrast. Quantifying robustness of contrast in using spectral analyses could increase the precision of researchers' and clinician's descriptions of children's articulation skills. Precise profiles of children's speech could lead to more informative normative data on the gradual acquisition process, more accurate diagnostic tools for describing covert contrasts, and more focused therapy approaches for children with speech sound disorders.

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