Articulatory, Perceptual, and Phonological Determinants of Accurate Production of /s/

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Abstract

Children's speech sound errors may reflect deficits in acoustic-phonetic, articulatory-phonetic, or phonological knowledge of those sounds. The purpose of the current study was to explore the factors believed to contribute to accurate articulation of /s/ in children with typically developing speech. Forty-eight children in their pre-kindergarten or kindergarten year participated. Acoustic-phonetic knowledge was assessed using a computer game targeting identification of correct and incorrect productions of /s/. Articulatory-phonetic skill was evaluated using maximum repetition tasks and by assessing stimulability for /s/. Phonological knowledge was assessed by examining the acoustic cues used by children to distinguish their productions of /s/ and /θ/. Acoustic-phonetic knowledge and phonological knowledge were each found to explain a small but significant amount of the variance in articulation accuracy. Three different perspectives regarding the relative importance of perceptual and articulatory skills in the development of phonological knowledge are discussed. Clinical implications of the results are considered.

Résumé

Les erreurs de prononciation chez les enfants peuvent indiquer des difficultés au niveau de la perception des paramètres phonétiques-acoustiques, des habiletés phonétiques-articulatoires ou de la connaissance phonologique des sons produits. Le but de ce projet de recherche était de déterminer quels facteurs peuvent contribuer à la prononciation exacte du son /s/ chez les enfants dont la parole se développe normalement. Quarante-huit enfants de niveau prématernelle et maternelle ont participé à l'étude. La perception des paramètres phonétiques-acoustiques a été évaluée en utilisant un jeu d'ordinateur. Les enfants devaient identifier les prononciations correctes et incorrectes du son /s/. Les habiletés phonétiques-articulatoires ont été évaluées en utilisant des mesures de la rapidité de répétition des syllabes et en évaluant la stimulabilité pour le son /s/. La connaissance phonologique a été évaluée en examinant les indices acoustiques qu'utilisent les enfants pour distinguer leurs productions de /s/ et /θ/. La perception des paramètres phonétiques-acoustiques et la connaissance phonologique permettent d'expliquer de façon significative une partie des différences de prononciation. Nous abordons l'importance relative des habiletés de perception et de prononciation dans le développement de la connaissance phonologique selon trois cadres théoriques. Les applications cliniques des résultats obtenus sont considérées.

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Introduction

Each time an individual produces a word, the accuracy of their production reflects their knowledge of the acoustic-phonetic, articulatory-phonetic, and phonological characteristics of that word. Knowledge in these three domains is accumulated gradually from birth and development can extend into late childhood, with typically developing children not attaining adult-like speech accuracy until the age of 8 years (e.g., Smit, Hand, Freilinger, Bernthal, & Bird, 1990). During development, children's productions, both those perceived as correct and those perceived as incorrect, often differ from those of adults. Even when a child's productions are judged to be correct, measurable differences continue to be present (Munson, 2004). As a result, some differences may not affect the listener's ability to understand what the child is intending to say, while other differences will noticeably affect the child's intelligibility. There are a number of reasons why a child's production of a word may differ from an adult's production of the same word. The following sections will provide an overview of the possible contributors to accurate articulation.

Contributions to Articulation Accuracy

Differences Which May Not Affect Intelligibility

Certain anatomical differences explain part of the difference between adult and child productions. The vocal tracts and vocal folds of young children are shorter than in adults, resulting in higher absolute and fundamental frequencies respectively (Kent, 1976; Kent & Read, 1992). Children's speech has been characterized by longer segmental durations and greater temporal and spectral variability than adult speech (Kent, 1976; Kent & Forner, 1980; Lee, Potamianos, & Narayanan, 1998; Munson, 2004). Kent (1976) reported a progressive decline in within subject variability in formant frequencies from 3- to 11-years, in fundamental frequency from 3- to 10-12 years, and in voice onset time (VOT) from 3- to 8-years of age. These high levels of variability are an indication of poor motor control, suggesting an inverse relationship between acoustic variability and articulatory control (Kent, 1976). It would seem that adult-like motor control may not be achieved until the age of 11- or 12-years, some time after the child's speech is perceived by listeners as accurate.

Maximum syllable repetition tasks involve repeating syllables or syllable sequences as quickly as possible and assess a speaker's ability to rapidly and precisely move their articulators. Children with typically developing speech tend to produce much slower repetition rates than adults until the age of puberty (Kent, 1997), with rates gradually increasing with age (e.g., Robbins & Klee, 1987).

Young children have been shown to organize their speech gestures differently than adults. Nittrouer, Studdert-Kennedy, and McGowan (1989) found that young typically developing children showed stronger fricative-vowel coarticulation than adults in reduplicated syllable productions, suggesting they organize their speech gestures in terms of syllables or words, in contrast with the segmental structure of adult speech.

Differences Affecting Intelligibility

Although the differences mentioned above may not substantially affect a listener's ability to understand what a child is intending to say, other differences can influence the perceived accuracy of a child's productions. These differences may result in errors perceived as speech sound substitutions, omissions, or distortions. Speech sound errors such as these occur in the speech of young typically developing children, as well as in children with speech sound disorders. Speech errors may reflect deficits in a child's acoustic-phonetic knowledge, articulatory-phonetic knowledge, or phonological knowledge of those sounds. We will now turn to a discussion of these knowledge areas, examining what deficits in each area can mean for a child's speech production.

Acoustic-Phonetic Knowledge. According to Edwards, Fourakis, Beckman and Fox (1999), the acquisition of acoustic-phonetic knowledge involves learning to attend to those aspects or components of the acoustic signal which serve to contrast sounds in one's language. Perceptual development thus involves learning what aspects of the speech signal are relevant given one's native language. This learning is believed to occur over the first 7 or 8 years of life (e.g., Nittrouer, 2002) as a result of experience with one's language.

Young children have generally been found to present with less mature perceptual strategies than adults. For example, they have been found to attend to different cues than adults during perception tasks (Nittrouer, 1992; 1996; 2002). Whereas adults focus on the acoustic cues associated with steady state portions of the stimuli (i.e., the fricative noise), young children have been found to attend largely to the dynamic spectral cues (i.e., formant transitions) associated with the syllable (Nittrouer, 1992; 1996; 2002). The perceptual performance of young children benefits from redundancy in the acoustic signal. Children are more consistent at identifying stimuli when there are several acoustic cues available than when fewer acoustic cues are used to signal a contrast (Hazan & Barrett, 2000). Finally, young children require more acoustic information and acoustic contrast than adults in order to discriminate between minimal pairs. Their performance suffers when acoustic information is digitally removed from the ends of natural recordings of minimally contrastive words (Edwards, Fox, & Rogers, 2002), and they require greater voice onset time (VOT) differences than older children and adults in order to discriminate between voiced and voiceless stops (Zlatin & Koenigsknecht, 1975).

When compared to their age-matched peers with typically developing speech, children with speech sound disorders have also been found to perform poorly on tests assessing speech perception. As with younger typically developing children, children with speech sound disorders are significantly less accurate than their typically developing peers at discriminating between minimal pairs when acoustic information has been digitally removed from the centre of words (Edwards et al., 1999) and from the end of words (Edwards et al., 1999; 2002). Their perceptual abilities are so fragile that even in conditions with very limited stress on their perceptual systems (e.g., loss of visual cues), their performance suffers (Edwards et al., 1999). While these authors propose general deficits in speech perception among children with speech sound disorders, other researchers have suggested that children with speech sound disorders have difficulty discriminating contrasts which involve the sounds they tend to misarticulate (Hoffman, Daniloff, Bengoa, & Schuckers, 1985; Rvachew & Jamieson, 1989).

Articulatory-Phonetic Knowledge. The acquisition of articulatory-phonetic knowledge involves learning which muscles to contract, how to finely coordinate the articulators, how to shape the vocal tract, and how to interpret efferent feedback when producing different sounds and words (Edwards et al., 1999). Accurate production requires detailed and flexible articulatory representations that allow the speaker to maintain accuracy in different contexts and when facing a range of task demands (Munson, Edwards, & Beckman, 2005b). Articulatory-phonetic knowledge is built incrementally as children gain experience using the words in their language (Edwards et al., 1999). We have already seen that the speech motor skills of young children are less developed than in adults. On average, children with speech sound disorders also demonstrate less mature speech motor control than their peers with typically developing speech. This finding has been replicated across a number of studies using a variety of assessment techniques.

Acoustic analysis allows one to make inferences regarding the relative position of vocal tract constrictions (Miccio, 1995). Edwards et al.'s (1999) acoustic analysis of children's speech revealed that children with speech sound disorders performed significantly differently than their typically developing peers on several spectral and temporal measures of their stop productions. The authors interpreted this finding as suggesting the children were less able to move their jaw and tongue body independently or else produced movements which were in general poorly controlled. Electropalatography (EPG) has revealed the use of undifferentiated lingual gestures in some children with speech sound disorders (Gibbon, 1999). These children demonstrate a lack of clear differentiation between the tongue tip/blade and the tongue body when producing lingual speech sounds, suggesting that they lack the control mechanism which allows the tongue tip/blade and tongue body systems to function relatively independently of each other (Gibbon, 1999). Measurement of speaking rate during nonmeaningful and meaningful speech tasks offers a more general measure of speech motor control. Children with speech sound disorders have difficulty with maximum repetition tasks (also known as diadochokinetic tasks) involving the repetition of mono-, bi- and tri-syllabic sequences (McNutt, 1977; Wolk, Edwards, & Conture, 1993). Although less well studied, children with speech sound disorders may also produce meaningful speech with slower articulation rates than children with typically developing speech (Flipsen, 2002).

While the assessment techniques discussed provide detailed information regarding speech motor control, a child's articulatory-phonetic knowledge also includes the ability to organize and combine a constellation of gestures in order to produce a specific sound. Stimulability refers to a speaker's ability to correctly imitate a sound. If a child can be stimulated to produce an accurate imitation of a target sound, this suggests that they do possess the physical ability to produce the sound (Edwards et al., 1999). However, stimulability also involves paying attention to the relevant characteristics of the model the child is being asked to imitate. It requires motivation on the part of the child to change their production of an incorrectly produced sound (Lof, 1996). Stimulability thus represents another possible method of evaluating a child's articulatory system, even though it is not a purely articulatory measure.

Phonological Knowledge. Although accurate and detailed acoustic and articulatory representations for words are fundamental to the development of a mature phonological system, a more abstract level of representation is also required. This higher level of phonological knowledge is instantiated in and abstracted from the underlying representations for words that are stored in the lexicon. This knowledge reflects the system of phonemic contrasts that are specific to the child's language as well as the phonotactic constraints that govern the legal combinations and ordering of phonemes that can be used to form words in that language.

The distinction between phonetic and phonological knowledge is clearly apparent in the discontinuity between infant perceptual abilities and early word learning abilities. Fourteen month olds are able to learn word-object pairings that involve dissimilar sounding 'words' such as [nif] and [lim]. Most children of this age are unable to learn word-object pairings when they involve phonetically similar 'words' such as [bɪ] and [dɪ] however, even though they are able to perceive this phonetic contrast (Werker, Fennell, Corcoran, & Stager, 2002).

Underlying phonological knowledge of a sound includes an understanding of the features which distinguish it from other sounds. Distinctive features can be viewed as switches which must be either turned on or off in order for a phoneme to be realized (Edwards, 1992). For example, interdental and alveolar fricatives are distinguished from palatal fricatives by the feature [+anterior] because they are produced in front of or at the alveolar ridge. Children need to learn which features to turn on and they develop this knowledge gradually as they gain experience with their native language (Edwards, 1992).

Traditionally, studies of normal and disordered speech have relied on perceptual analyses to make inferences about underlying phonological knowledge. Perceptual analysis involves listening to, judging, and phonetically transcribing productions. However, an analysis based solely on phonetic transcription may not identify all that a child knows about a sound or phonemic contrast (Miccio, 1995). Some children produce imperceptible contrasts or covert contrasts which are instrumentally measurable differences between phonemes that are otherwise imperceptible to listeners (Baum & McNutt, 1999; Forrest, Weismer, Hodge, Dinnsen, & Elbert, 1990; Gibbon, 1999; Miccio, 1995). Forrest et al. (1990) conducted a spectral moments analysis of word-initial voiceless stops. They found that of the four children in their study who produced [t] for /k/, one child distinguished his productions acoustically, albeit using different cues than those used by children with typically developing speech. This child's knowledge of the /k/-/t/ contrast was obviously different from the knowledge of the other three children who did not distinguish their productions on any acoustic cue.

Instrumental analysis is also useful for revealing information regarding productions perceived by listeners as correct. Young children demonstrate smaller differences between their centroid values for /s/ and /ʃ/ than adults (Nittrouer et al., 1989; Nittrouer, 1995). Nissen and Fox (2005) also found that children's /s/ and /ʃ/ productions were not acoustically differentiated in the same way as adult productions. Children with speech sound disorders do not always use the same acoustic cues as their typically developing peers to signal phonemic contrasts, even after they have learned to produce a perceptually correct contrast (Forrest et al., 1990; Miccio, 1995).

The above studies suggest that regardless of whether or not a child's production of a sound is perceptually correct, discontinuities between phonological and phonetic knowledge can exist. As we have seen, covert contrasts occur in children who produce contrasts between phonemes that are not realized in terms of standard phonetic cues and therefore are not perceived by listeners. However, there are also examples of children who maintain a phonetic contrast which is perceptible to listeners, but do so using non-adult-like acoustic cues. Instrumental measures, such as acoustic analysis, have the potential to reveal information about children's productions that is not revealed by perceptual analysis alone.

The literature review thus far reveals that acoustic-phonetic knowledge, articulatory-phonetic knowledge, and phonological knowledge contribute to the accuracy of speech sound production. However, no study has examined the contribution of all three factors to the production of a specific sound contrast within the same children. The purpose of this thesis research is to examine the contribution of these three types of knowledge to the acquisition of a fricative contrast (/s/ vs /θ/) within a group of children with typically developing speech.

As a prelude to outlining the specific hypotheses that guide this study, a review of the literature relating to the development of voiceless fricatives follows.

Voiceless Fricatives

Fricatives represent a class of later developing sounds. For example, the alveolar fricative (/s/) has an age of mastery of 7- to 9-years for both girls and boys (Smit et al., 1990). In his review of the literature on the acquisition of fricatives, Ferguson (1978) reported on a number of findings regarding fricative development, including the suggestion that fricatives represent a late developing sound class because of the articulatory and perceptual problems they pose.

Many of the studies examining the acoustic characteristics of fricative productions have focused on the sibilant sounds /s/ and /ʃ/ (e.g., Newman, Clouse, & Burnham, 2001; Nittrouer, 1995; Nittrouer et al., 1989; Perkell et al., 2004b). Fewer studies have examined the sibilant/nonsibilant distinction (/s/ versus /θ/). It is common to observe errors involving this contrast among children. By the age of 6-years, almost all /s/ errors are dental: either dental [s̪], [θ] substitution, or slight dentalization (Smit et al., 1990). The next section will review the acoustic-phonetic, articulatory-phonetic, and phonological characteristics of the voiceless fricatives /s/ and /θ/.

Acoustic-Phonetic Characteristics of /s/ and /θ/

The voiceless fricatives in English can be distinguished from one another on a number of cues: duration of the fricative noise, amplitude of the noise, spectral properties of the noise. The alveolar fricative is longer in duration than the interdental fricative and productions of /s/ are higher in amplitude (Baum & McNutt, 1990; Jongman, Wayland, and Wong, 2000; Kent & Read, 1992). The spectral shape of each fricative is determined by the size and shape of the oral cavity in front of the constriction (Jongman et al., 2000; Pickett, 1999). The smaller the front cavity is, the higher in frequency the position of the strongest resonances (Picket, 1999). As a result, studies examining fricatives in adults have revealed that the strongest resonances for /s/ are in the region around 4kHz and in the region around 5kHz for /θ/ productions (Pickett, 1999). The alveolar fricative displays a primary spectral peak around 4 to 5 kHz, while /θ/ has been described as having a flatter spectrum (Jongman et al., 2000). Children who experience difficulty producing the /s/-/θ/ contrast may do so because they are unable to perceive the acoustic differences between /s/ and /θ/.

Articulatory-Phonetic Characteristics of /s/ and /θ/

Both fricatives are both produced by forming a narrow constriction at a certain point in the oral tract, creating a partial blockage of the air stream. As air flows through this constriction, turbulence or frication is created (Kent & Read, 1992). In order to produce a reliable contrast between /s/ and /θ/, the child must learn that these two sounds differ with respect to the location of the constriction. For /θ/, the constriction is created when the tongue tip contacts or goes between the teeth whereas for /s/, the constriction involves raising the tongue blade to the alveolar ridge (Edwards, 1992). The child must also realize that in order to produce an accurate /s/, the front of the tongue blade must form a groove in the region of the alveolar ridge while the bottom of the tongue tip contacts the lingual aspect of the lower incisors (Perkell et al., 2004b). The lateral borders of the tongue must also form a seal along the upper gums or between the upper and lower teeth (Gibbon, Hardcastle, & Dent, 1995). Children who have difficulty producing the /s/-/θ/ contrast may do so because they have difficulty with or are unaware of the articulatory gestures required to differentiate the two sounds.

Phonological Knowledge of /s/ and /θ/

For the purpose of this research, the nonlinear feature system described by Bernhardt and Stemberger (1998) will be used.

An adult's underlying phonological knowledge of the fricatives /s/ and /θ/ includes an understanding of the features which distinguish the two sounds. Whereas both fricatives can be described as [+consonantal], [+continuant], coronal, and [+anterior], the interdental fricative is distinguished from the alveolar fricative based on the distinctive feature [+distributed] (Bernhardt & Stemberger, 1998). Coronal sounds produced with the tongue blade are [+distributed], whereas coronal sounds produced with the tongue tip are [-distributed]. When a child fails to produce a reliable distinction between /s/ and /θ/, it may be because they do not yet realize that the marked feature [+distributed] needs to be turned on for the contrast to be realized. They may instead possess a single phonetic target for the two phonemes.

However, it is also possible for children to produce an imperceptible (i.e., covert) contrast between /s/ and /θ/, suggesting that they possess some knowledge of the features required for the contrast to be realized. Children who misarticulate /s/ (i.e., produce dentalized distortions or [θ] substitutions for /s/) have been shown to distinguish their productions of these sounds using duration, amplitude, and centroid values, suggesting they may possess distinct representations for the two phonemes (Baum & McNutt, 1990). Children with typically developing speech have also been shown to distinguish between nonsibilant (i.e., /θ/ and /f/) and sibilant sounds (i.e., /s/ and /ʃ/) acoustically. Miccio (1995) found that typically developing children used centroid, skewness, and kurtosis to signal the /s/-/θ/ contrast, even when they were not yet producing a perceptually correct /θ/.

These studies of fricative production in children with typical or delayed speech development show that, in some cases, inaccurate production of the /s/ and /θ/ sounds reflects the absence of abstract underlying knowledge of this phonemic contrast. However, even those children who demonstrate underlying knowledge of these phonemes, through the presence of a perceptually obvious or covert contrast, may not produce these phonemes with mature phonetic characteristics. In these cases, it is not clear whether immature production of the /s/ and /θ/ phonemes reflects inaccurate acoustic-phonetic representations (i.e., poor perceptual knowledge of the relevant acoustic cues) or inaccurate articulatory-phonetic representations (i.e., poor articulatory knowledge of the required articulatory gestures). Different perspectives regarding the relative importance of perceptual and articulatory skills in the development of phonological knowledge will be discussed in the next section.

Theories of Phonological Development

A number of researchers have suggested a central role for speech perception in phonological development (e.g., Echols, 1993; Perkell et al., 2004a; Rvachew, 1994; Rvachew & Jamieson, 1989; Rvachew, Nowak, & Cloutier, 2004; Velleman, 1988). Others emphasize the role of articulation (e.g., Newman, 2003; Sénéchal, Ouellette, & Young, 2004; Thomas & Sénéchal, 1998; 2004), while others still describe phonological development as involving the acquisition of both perceptual and articulatory knowledge and the mappings between the two (e.g., Beckman & Edwards, 1999; Edwards, Beckman, & Munson, 2004; Edwards et al., 1999; Munson, Edwards, & Beckman, 2005a; 2005b).

Speech Perception in Phonological Development. Children usually perceive words accurately before they can accurately produce them (Bernhardt & Stemberger, 1998). Infants as young as 10-12 months are able to discriminate between the consonant and vowel distinctions which are used to distinguish meaning in their language, they are aware of the stress patterns and phonotactic regularities of their language, and they can use their phonetic and prosodic knowledge to segment the incoming speech stream (Werker et al., 2002). Fourteen month old infants are able to use their perceptual abilities to discriminate between phonetically similar words, and by 17 months are able to use this perceptual knowledge when learning new words (Stager & Werker, 1997; Werker et al., 2002). Models which emphasize the role of perception in the development of articulation accuracy suggest that children first develop perceptual knowledge of a phoneme and then attempt to match their productions to their underlying perceptual representations. According to such models, poor speech perception leads to inappropriate underlying phonological representations, resulting in inappropriate targets for production.

Support for such models is provided by studies examining the relationship between perceptual skills and articulation accuracy. For example, perceptual salience has been found to contribute to the production errors of some young children. Echols (1993) found that syllables which were less perceptually salient (i.e., unstressed or non-final) were incompletely extracted and stored in children's underlying representations, resulting in production errors. Velleman (1988) found a significant correlation between children's perception and production of /θ/ but not /s/. She described /θ/ errors as being perceptually based and /s/ errors as phonetically based. She suggested this was because /θ/, but not /s/, was often difficult to discriminate from other fricatives.

The relationship between perception and production has also been examined in adults. Perkell et al. (2004a) found that adults who were more accurate at discriminating vowel contrasts produced more distinct vowel contrasts as measured by both articulatory parameters (i.e., differences in tongue body position for each vowel) and acoustic parameters (i.e., distance between mean values of F1 and F2 for each vowel). The authors interpreted these findings within the framework of the DIVA model of speech motor planning (e.g., Guenther, 1995). According to this model, the goals for vowel movements consist of regions in auditory-temporal space. Speakers' auditory goals are formed by listening to sounds and constructing appropriate boundaries in acoustic-phonetic space. These regions are then used both in perception and as the goals for speech motor planning. During language learning, speakers who are able to perceive fine acoustic-phonetic details may be better able to reject poor exemplars of a phoneme and thus learn auditory goal regions that are smaller and spaced further apart. The size and distance between these goal regions determine how distinct and intelligible a speaker's productions are (Perkell et al., 2004a).

Speech perception ability is a significant contributor to and longitudinal predictor of articulation accuracy. Using linear structural modeling, Rvachew & Grawburg (in press) found that speech perception explained 21% of the variance in articulation accuracy in preschoolers. Furthermore, Rvachew (in press) found a stronger relationship between pre-kindergarten speech perception and kindergarten articulation than between pre-kindergarten speech perception and pre-kindergarten articulation. Pre-kindergarten speech perception explained 8% of the variance in kindergarten articulation skills after controlling for pre-kindergarten articulation skills.

Further research confirming the critical role speech perception plays in the development of accurate speech production is provided by experimental studies examining the relationship between speech perception training and articulation accuracy (Jamieson & Rvachew, 1992; Rvachew, 1994; Rvachew et al., 2004). Rvachew and colleagues have shown that children with speech sound delays demonstrate greater gains in articulatory accuracy following concomitant speech perception training and speech production training (Rvachew, 1994; Rvachew et al., 2004). Perception training without articulation therapy can also lead to improvements in articulation accuracy (Jamieson & Rvachew, 1992). Rvachew and colleagues suggest that speech perception training is successful because it provides the child with more accurate acoustic representations of the phoneme categories, thus providing them with more accurate targets for speech production.

Articulation in Phonological Development. In contrast, several researchers favour the role of articulation in phonological development. According to such models, articulation is believed to lead perception developmentally, even though articulatory accuracy in the absence of perception abilities in development is rare.

Certain researchers propose a model in which the quality of underlying representations affects the accuracy of children's articulations, which subsequently 'feed back' and either strengthen or weaken the representations. Inaccurate articulation limits the development and/or refinement of underlying representations, which then affects speech perception skills, articulation accuracy, and phonemic awareness (Sénéchal et al., 2004; Thomas & Sénéchal, 1998; 2004). Sénéchal et al. (2004) found that articulation accuracy of /r/ was related to speech perception and phonemic awareness of the same phoneme in typically developing preschoolers, even after controlling for age, vocabulary level, beginning reading skills, speech perception of control phonemes, and phoneme awareness. Articulation accuracy explained 22% of the variance on one of their speech perception measures.

The same sound can be articulated in different ways by different people. How an individual produces a sound might influence what they expect to hear when others produce that sound (Newman, 2003). Newman found a significant relationship between participants' productions and their perceptual prototypes (i.e., the item with the highest mean rating based on listeners' ratings of items for their goodness as members of a phoneme category). Participants whose perceptual prototype of the /p/ in /pɑ/ occurred at longer VOT were those who produced /pɑ/ with longer VOT. Similarly, listeners whose /ʃ/ productions showed more extreme peak frequency values preferred to listen to /ʃ/ tokens with more extreme peak values. The correlations between production and perception were significant, and production was found to account for 27% of the variance in perception.

Representation-Based Model of Phonological Development. A more recent theory of phonology is the representation-based approach. In contrast with traditional, modular rule-based models of phonology, representation-based approaches consider phonological knowledge as a multilayered hierarchy consisting of complex representational spaces and the mappings between them (Beckman & Edwards, 1999; Edwards et al., 1999; Pierrehumbert, 2003). According to this approach, phonological knowledge consists of acoustic/perceptual knowledge, articulatory/productive knowledge, and the inverse mappings between perception and production (Edwards et al., 1999).

It has been suggested that difficulties experienced by children with speech sound disorders may be at least partly the result of weak cognitive representations of the perceptual cues for speech sounds or of the motor control structures needed for production (Edwards et al., 1999). As already discussed, Edwards et al. found that children with speech sound disorders required more acoustic information than typically developing children to recognize familiar words and differed significantly from their peers on several spectral and temporal measures obtained from their recorded speech productions. Acoustic-phonetic and articulatory-phonetic knowledge have also been examined in adults. Perkell et al. (2004b) examined how sibilant discrimination and tongue-to-alveolar ridge contact patterns during sibilant production were related to the degree of acoustic contrast (measured using centroid) between participants' productions of /s/ and /ʃ/. Participants who were found to use greater contact difference when producing /s/ and /ʃ/ (i.e., high differential contact) and who were better able to perceive fine acoustic differences between /s/ and /ʃ/ (i.e., high perceptual acuity) tended to produce sibilants that were the most acoustically distinct.

The third component of phonological competence is the inverse mapping between perceptual and productive knowledge (Beckman & Edwards, 1999; Edwards et al., 2004; Munson et al., 2005a). A child's expressive vocabulary contains only those words for which the child possesses both a detailed articulatory/productive representation and an acoustic/perceptual representation. In order for a child to acquire a new word, the child must perform a 'fast-mapping' between their knowledge representations in these two domains. When a child hears a novel word they will attempt "to identify its sequences of consonant and vowel events with the practiced gestures and synchronizations that produce sequences in known words" (Beckman & Edwards, 1999, p. 212). Consequently, if a new word contains a familiar sequence and thus a familiar arrangement of gestures, it should be imitated more accurately and fluently, in contrast with a new word containing an unfamiliar sequence. This has been illustrated in studies showing that accuracy of non-word repetition is significantly influenced by the frequency of occurrence of the non-words' sublexical (i.e., two-phoneme sequences) components in children with typically developing speech (Edwards et al., 2004) and in children with speech sound disorders (Beckman & Edwards, 1999; Munson et al., 2005a).

These findings are offered as support for the proposal of representation-based approaches that children with speech sound disorders differ from their typically developing age-matched peers on all three components: perceptual knowledge, articulatory knowledge, and the mapping between the two (Edwards et al., 1999; Munson et al., 2005a; 2005b). However, to date, no research motivated by representation-based approaches of phonology has examined both perception and production of the same sound contrasts in children.

Purpose of the Current Study

Employing *global* measures of speech perception and production, Rvachew and Grawburg (in press) found that speech perception was able to explain 21% of the variance in articulation accuracy. The present study attempted to replicate and extend this finding by examining perception and production of a *specific* phoneme, and by seeking to determine whether the child's ability to manipulate the articulators precisely and the child's underlying phonological knowledge of the sound helped to explain some of the remaining variance in articulation accuracy. Acoustic-phonetic knowledge of the target phoneme was assessed using a measure of speech perception. Articulatory-phonetic knowledge was evaluated by i) using maximum repetition tasks and by ii) assessing the child's stimulability for the target phoneme. Phonological knowledge was assessed by i) calculating the percent correct production of the target phoneme on a word naming probe to obtain a measure of articulation accuracy, and by ii) examining acoustic differences between the children's productions of the target sound and a sound commonly substituted for the target.

Hypotheses

Accurate articulation requires knowledge in each of the three above mentioned areas. The goals of the current study were thus to demonstrate that acoustic-phonetic, articulatory-phonetic, and phonological knowledge are necessary for accurate articulation, further examining the hypotheses put forth by the three theories discussed above:

Speech Perception Hypothesis. Speech perception skills will explain a significant portion of the variance in articulation accuracy. Articulation will not be found to explain any unique variance when speech perception is controlled.

Articulation Hypothesis. Measures of articulatory precision will explain a significant portion of the variance in articulation accuracy, whereas speech perception will not be found to explain any unique variance when articulation is controlled.

Representation-Based Hypothesis. Measures of speech perception and of articulation will independently contribute to variance in articulation accuracy.

Method

Participants

Sixty-nine children were recruited from local daycares and schools by sending letters home to parents. It was not possible to recruit monolingual English children. However, children were judged to be proficient in English based on their performance on the Peabody Picture Vocabulary Test-Third edition (PPVT-III: Dunn & Dunn, 1997) and based on the examiner's observations. Only children who scored within normal limits (i.e., 16^{th} percentile or higher) on the Goldman-Fristoe Test of Articulation-Second edition (GFTA-2; Goldman & Fristoe, 2000) were included in the final data set. The data for three children were lost due to withdrawal from the study as a result of family illness (n = 1) or inability to schedule a second assessment (n = 2); the data for 11 children were lost due to high levels of background noise at the time of testing; data were incomplete for two children because they experienced difficulty meeting the demands of the tasks; five children were excluded because they scored below the 16^{th} percentile on the GFTA-2. From here on, only information and results pertaining to the final data set of 48 children will be discussed.

The characteristics of the children in the final data set are shown in Table 1. The participants were 31 males and 17 females ranging in age from 51 to 86 months on the day of their first assessment. All participants demonstrated receptive vocabulary skills within normal limits with the exception of two children who obtained standard scores of 78 and 84 on the PPVT-III. All participants had normal hearing and oral structure as determined by observation

Table 1

Means and Standard Deviations of Participant Characteristics and Test Scores (n=48)

Participant Variables	*M*	*SD*
Age	65.88	7.69
PPVT-III	109.02	12.97
GFTA-2	102.88	8.22
Maternal Education	16.89	2.43

Note. Age is in months; PPVT-III = Peabody Picture Vocabulary Test- Third Edition, standard score; GFTA-2 = Goldman-Fristoe Test of Articulation- Second Edition, standard score; Maternal Education = mean number of years of maternal education.

and/or parental report. For each participant, the level of maternal education was obtained. With the exception of one mother whose highest level of education was secondary school completion, all of the children's mothers had college diplomas or university degrees.

Target Phonemes

The factors contributing to articulation accuracy were examined by assessing perception and production of /s/. The alveolar fricative was chosen as the target sound in this study as it is a later acquired phoneme with an age of mastery of 7-9-years for both girls and boys (Smit et al., 1990). As already mentioned, it is common to find errors involving dentalization of /s/ productions in children within the age range of the participants in the current study.

Procedure

Each child was assessed individually in a quiet room within their daycare or school, or in the house of the author's supervisor. Many participants were simultaneously enrolled in another study. Testing for both studies was usually carried out on the same day, with many breaks offered to the children. Assessments specific to the current study consisted of two 30-45 minute sessions.

Acoustic-Phonetic Knowledge

The preciseness and specificity of the children's acoustic-phonetic knowledge of the target phoneme was assessed using the Speech Assessment and Interactive Learning System (SAILS; AVAAZ Innovations). SAILS is a computer game which assessed the child's ability to identify sounds that were pronounced correctly and sounds that were pronounced incorrectly within the context of a word. The SAILS stimuli were recorded from both children and adults and were digitized at a sampling frequency of 20 kHz with a 16-bit quantization rate. Half of the stimuli were pronounced correctly (e.g., *Sue* → [su]) and the other half incorrectly (e.g., *Sue* → [ʃu]). The words were presented one at a time over headphones and children were provided with two response alternatives: a picture of the target word and an X. In order to assess perception of /s/, SAILS modules targeting the word *Sue* were presented to each child (as part of a larger study, perception of /f/ was also assessed). For example, children were instructed to point to the picture of the girl 'Sue' if they heard the word *Sue*, and to the X if they heard a word that was '*not Sue*' (e.g., [θu,ʃu,tʃu,du,tsu,sju,s^{l}u]). A child who identifies both [su] and [θu] as exemplars of the word *Sue* has a less detailed perceptual representation of this word than a child who would respond that [θu] is "not Sue". Prior to starting the test trials, each child received 10 practice trials during which they were provided with corrective feedback and further instruction if needed. The 'Sue' stimuli were divided into three levels of 10 stimuli each, with the level of difficulty increasing from level 1 to 3. Level 1 contrasted correct /s/ productions with stop (e.g., [tu]) and affricate (e.g., [tʃu]) substitutions. Level 2 contrasted correct /s/ productions with fricative substitutions (e.g., [θu, ʃu]). Level 3 contrasted correct /s/ productions with /s/ distortions (e.g., [s^{l}u]). Each child was presented with the three levels on both assessment visits. Sixty /s/ items (30 per session) were presented, not including the practice trials.

Articulatory-Phonetic Knowledge

Each child's articulatory-phonetic skill was examined by assessing their ability to manipulate the articulators during non-meaningful speech. This was accomplished using *Maximum Performance Tasks* (MPT). Using the computer based software TOCS (Hodge & Daniels, 2004) and following the instructions provided in Thoonen, Maassen, Wit, Gabreëls, and Schreuder (1996), four MPTs were administered: maximum monosyllabic repetition rate (MRR), maximum trisyllabic repetition rate (TRR), maximum phonation duration, and maximum fricative duration (for a tutorial on using TOCS to measure MPTs see Rvachew, Hodge, & Ohberg; 2005). The MRR involved instructing the child to produce the syllables 'papapa', 'tatata', and 'kakaka' as fast as they could. The TRR involved asking the child to produce the syllable sequence 'pataka' as fast as they could. These tasks assessed the coordinative ability of the lips and tongue to produce repetitive movements as quickly as possible (Thoonen et al., 1996). Following instruction, each participant received three attempts to produce their maximum performance on each task. An additional three attempts were provided if needed in order to produce a correct trisyllabic sequence. The maximum phonation duration tasks required the child to produce a sustained 'ah' and a prolonged repetition of the sequence 'mama'. For the maximum fricative duration, the child prolonged /f/, /s/, and /z/ for as long as possible. The maximum phonation and fricative duration tasks assessed the phonatory and respiratory capacities of the children (Thoonen et al., 1996). Only performance on the MRR and TRR were considered for the purposes of this study (for a preliminary examination of the performance of a subgroup of these children on all four MPT tasks see Rvachew, Ohberg, & Savage; 2006). The TOCS software directly recorded the children's productions into .wav files. It provided the option of playing back children's recorded productions, a feature which was helpful in maintaining their interest throughout the tasks.

The children's productions from the maximum performance tasks were entered into the Time Frequency Response software (TFR; AVAAZ Innovations) for analysis. For the maximum repetition rate tasks, analysis was carried out according to Thoonen et al. (1996). Syllable boundaries were determined using both auditory information and visual inspection of the waveform. The onset of syllables was identified by locating the burst of the voiceless stops (i.e., high amplitude followed by a period of relative silence). The MRR was calculated for 10 syllables, the TRR was calculated for 12 syllables. Each attempt on each of the maximum performance tasks was measured and a summary value was calculated from the average of their best performances. Both the MRR and the TRR tasks are reported in syllables per second.

Stimulability represents another possible indicator of articulatory-phonetic knowledge. Stimulability for /s/ was assessed by examining each child's phonetic repertoire. Phonetic repertoires were based on children's productions on two measures of productive phonological knowledge (GFTA-2 and an articulation probe). The maximum fricative duration task was also used to determine if the children were stimulable for /s/ in isolation. During this task, the children were provided with models before being asked to produce prolonged /s/ themselves.

Phonological Knowledge

The child's phonological knowledge of /s/ was assessed using a single word articulation probe designed to elicit production of /s/ and /θ/ in the onset of near minimal CVC pairs. Both perceptual and acoustic analyses were performed on children's productions in order to assess the accuracy of each child's production of /s/, as well as their ability to consistently distinguish their /s/ productions from the interdental voiceless fricative. It is assumed that the ability to consistently distinguish between target /s/ and /θ/ productions phonetically indicates underlying knowledge of the contrast. This is not to say that the underlying representation is adult-like, or that the feature [+distributed] is acquired.

The items chosen to contrast these phonemes in the onset were *sick* and *thin* (as part of a larger study, the labiodental fricative /f/ was also assessed). The children were presented with pictures depicting these items. The children were instructed to name each picture as it was presented. Each picture was preceded by a cloze sentence provided by the examiner: "This boy is not feeling well, he is feeling___(sick)" and "This pencil is thick, this pencil is ___(thin)". If a picture was incorrectly named, the child was provided with a model which they were asked to repeat. The pictures were presented to the child in random order. Each child was presented with each picture 10 times.

Acoustic Analysis. Children's productions were recorded using a SONY Minidisk recorder and Sennheiser lapel microphone (MKE 2) placed approximately 12 cm away from the child's mouth. Recordings were digitized at a

40 kHz sampling rate using TFR (AVAAZ Innovations) and acoustic analysis was carried out to examine acoustic differences between target /s/ and /θ/ productions.

Both centroid and duration measures were used by Munson (2004) in his examination of variability in /s/ productions in children and adults, by Baum and McNutt (1990) in their examination of covert contrasts, and by Perkell et al. (2004b) to measure the acoustic distinction between /s/ and /ʃ/ in adults. Centroids are believed to reflect front cavity resonances, have been found in previous studies with adults to distinguish among the four fricative places of articulation in English (e.g., Jongman et al., 2000), and have been used in studies examining children's fricative productions (e.g., Nittrouer 1995). As a result, it was decided that centroid would represent the main acoustic cue examined in the current study, with duration also being measured. However, Flipsen, Shriberg, Weismer, Karlsson, and McSweeny's (1999) review of the research on the acoustic characteristics of /s/ revealed that the first (i.e., centroid) and third (i.e., skewness) moments taken from the midpoint of the fricative noise were very important for characterizing /s/. Newman et al. (2001) found that centroid and skewness values were useful for distinguishing /s/ and /ʃ/ in adults. Miccio (1995) found that the typically developing children in her study used centroid, skewness, and kurtosis to distinguish between nonsibilants and sibilants. It was therefore decided to also examine children's skewness and kurtosis values.

Each child produced 10 *sick* tokens and 10 *thin* tokens. Analysis was conducted on all tokens for most participants. However, some tokens were excluded for some children because of background noise occurring during the fricative production. Linear predictive coding (LPC) was used in the analysis of the fricative productions. Following from Flipsen et al.'s (1999) conclusions regarding the acoustic analysis of /s/, a 20 ms window placed at the fricatives' midpoint was used. The onset of aperiodic, high frequency noise was taken as the fricative onset. As in Munson (2004), the end of the fricative was defined as the end of the aperiodic noise, regardless of whether the end of the fricative was slightly voiced, or the vowel partially voiceless.

For each child, mean centroid, duration, skewness, and kurtosis values and the standard deviation of these values were calculated. According to Newman et al. (2001), knowledge of a cue's variability is as important as knowledge of its mean value. As already mentioned, Newman et al. found that both centroid and skewness were useful cues for differentiating between /s/ and /ʃ/. However, they also found a considerable amount of overlap between participants' productions of the two sounds. A cue's usefulness for distinguishing between two phonemes depends at least in part on the amount of cue variability or overlap in their distributions. Newman et al. concluded that talkers who have phoneme categories which are very distinct from each other as well as highly internally consistent have more consistent productions and are more intelligible to listeners. In order to evaluate each child's underlying phonological knowledge of the /s/-/θ/ contrast, the degree of difference measure used in Newman et al. was used for the current study. This measure is $d_{(a)}$ and is a measure of sensitivity in signal detection theory. $D_{(a)}$ is equal to the difference in the means of the two categories times the square root of two, divided by the square root of the sum of the variances. This measure thus takes into consideration both the distance between a speaker's categories (i.e., target /s/ and /θ/) and the variability within each category.

Perceptual Analysis. In order to evaluate articulation accuracy, the children's productions on the articulation probe were phonetically transcribed. The number of /s/ items perceptually judged to be correct by the author was obtained from the phonetic transcription. Substitutions (e.g., [θɪk] for /sɪk/) and distortions (e.g., [s̪ɪk, sˡɪk]) were counted as /s/ errors.

Data Analysis

Means and standard deviations were calculated for each child on each measure. Correlational analyses were performed to examine the relationship among these variables. An alpha level of .05 was used when conducting all statistical analyses. Hierarchical multiple regression analyses were also carried out in order to determine which variables predicted articulation accuracy of /s/. The independent variables entered into the analysis were the measure of articulatory-phonetic skill (MRR and TRR), the measure of acoustic-phonetic knowledge (SAILS), and the measure of phonological knowledge of the contrast (i.e., $d_{(a)}$). The dependent variable in the model was /s/ articulation accuracy on the single word articulation probe.

Reliability

Split-half reliability, previously calculated for SAILS and based on perception of a number of commonly misarticulated sounds by 35 children, is .82 (Rvachew & Grawburg, in press). Twenty percent (10 children) of the current sample was randomly selected for transcription of the /s/ articulation probe by a second observer. Interjudge percent agreement for correct versus incorrect /s/ productions on the single word probe was 83%. In the case of disagreement, the initial transcription was maintained as it was based on both visual and acoustic information. Twenty percent of the sample was also randomly selected to be acoustically analyzed by a second observer. Average measure intraclass correlations were .9966 and .9217 for /s/ and /θ/ centroid values respectively; .9956 and .9331 for /s/ and /θ/ duration values respectively; .9956 and .9831 for /s/ and /θ/ skewness values respectively; and .9896 and .9900 for /s/ and /θ/ kurtosis values respectively.

Results

Descriptive Results

The outcome measure in this study was articulation accuracy, assessed using the single word articulation probe and expressed as the percent correct target /s/ productions. The goal of the current study was to evaluate the contributions of acoustic-phonetic knowledge, articulatory-phonetic knowledge, and phonological knowledge to articulation accuracy. Table 2 shows the results for all 48 children on the predictor and outcome measures. Individual results for these tasks can be found in Table A1 of Appendix A.

Acoustic-Phonetic Knowledge

Acoustic-phonetic knowledge was assessed using the SAILS task of speech perception. As can be seen from Table 2, the children as a group obtained a mean score of 71.16% on this test. Previous studies using this task have used a score of 70% as a criterion for separating children into groups with good versus

Table 2

Means, Standard Deviations, and Range of Scores Obtained on all Predictor and Outcome Measures (n=48)

	M	*SD*	Minimum	Maximum
SAILS	71.16	7.83	53.33	86.67
MRR	4.52	0.44	3.03	5.28
TRR	4.54	0.89	3.08	6.74
$d_{(a)}$centroid	1.08	1.70	-1.27	8.28
$d_{(a)}$duration	1.09	1.37	-1.19	5.61
Probe /s/	65.63	38.70	0.00	100.00

Note. SAILS = Speech Assessment and Interactive Learning System, percent correct; MRR = Monosyllabic Repetition Rate, syllables per second; TRR = Trisyllabic Repetition Rate, syllables per second; $d_{(a)}$centroid = degree of separation between /s/ and /θ/ centroid distributions; $d_{(a)}$duration = degree of separation between /s/ and /θ/ duration distributions; Probe /s/ is the percent correct of /s/ productions on the single word articulation probe.

poor speech perception (e.g., Rvachew et al., 2004). The group's performance on each level of SAILS was examined. A repeated measures ANOVA (general linear model) was applied to the data. The within-subject effect of SAILS level was significant [$F(2, 94) = 94.579, p = .000$]. As can be seen from Figure 1, children's speech perception skills were more accurate for level 1 than for levels 2 and 3. Cronbach's alpha was used to assess the internal consistency of SAILS across the two assessment times and was found to be .80.

Articulatory-Phonetic Knowledge

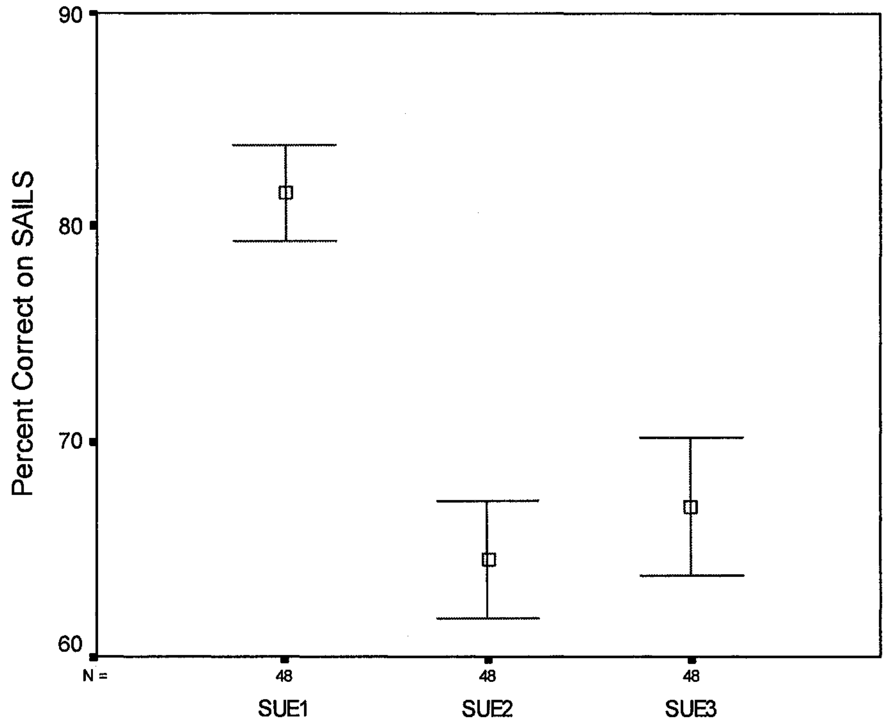
Articulatory-phonetic skills were assessed using two maximum performance tasks: MRR and TRR. Results for these tasks are presented in Table 2. Three children were unable to produce a correct sequence on the TRR task so results for this task are based on 45 of the total 48 children. Most of the children performed as expected given their age, although some children produced rates that were slightly lower than expected (Robbins & Klee, 1987). Stimulability was also evaluated. Children were classified as unstimulable if they obtained a score of zero on the /s/ articulation probe, if their /s/ productions on the GFTA-2 were inaccurate, and if they were unable to produce a correct /s/ in isolation during the maximum fricative duration task. Seven children were judged to be unstimulable.

Phonological Knowledge

Phonological knowledge was assessed using both perceptual and acoustic measures. The results of the acoustic analysis provided a measure ($d_{(a)}$) that was used to determine whether the children possessed underlying knowledge of the contrast between /s/ and /θ/. The perceptual analysis, which allows one to make

Figure 1

Mean Group Performance on Each Levels of SAILS



inferences about underlying phonological knowledge, provided a measure of articulation accuracy. Results from both types of analyses are discussed.

Acoustic Analysis. Centroid, duration, skewness, and kurtosis values were obtained from acoustic analysis of the children's target /s/ and target /θ/ productions on the articulation probe. For each child, the means and standard deviations of these cues were calculated. Raw acoustic data can be found in Appendix A. Table 3 shows the group mean, standard deviation, and range for these cues. As expected, mean /s/ centroid values were lower than mean /θ/ centroid values and mean /s/ durations were longer than mean /θ/ durations. Also as expected, there was a considerable degree of variability in centroid and duration values, resulting in overlap between /s/ and /θ/ distributions. Mean skewness values for /θ/ were negative, while the mean skewness values for /s/ were positive. Mean kurtosis values for /s/ were greater than for /θ/. As can be seen from Figure 2, both skewness values (r = -.846, p =.000) and kurtosis values (r = .613, p = .000) tracked very closely with centroid values and did not tell us more about children's knowledge of this contrast. As a result, the remainder of the analyses focused only on centroid and duration values.

Perceptual Analysis. Performance on the single word articulation probe was calculated as the percentage of correct /s/ productions. Scores ranged from 0% to 100%. The majority of children's errors (91.52% of errors) involved /s/ productions that were judged to be either [θ] for /s/ substitutions or dentalized [s̪] distortions.

Table 3

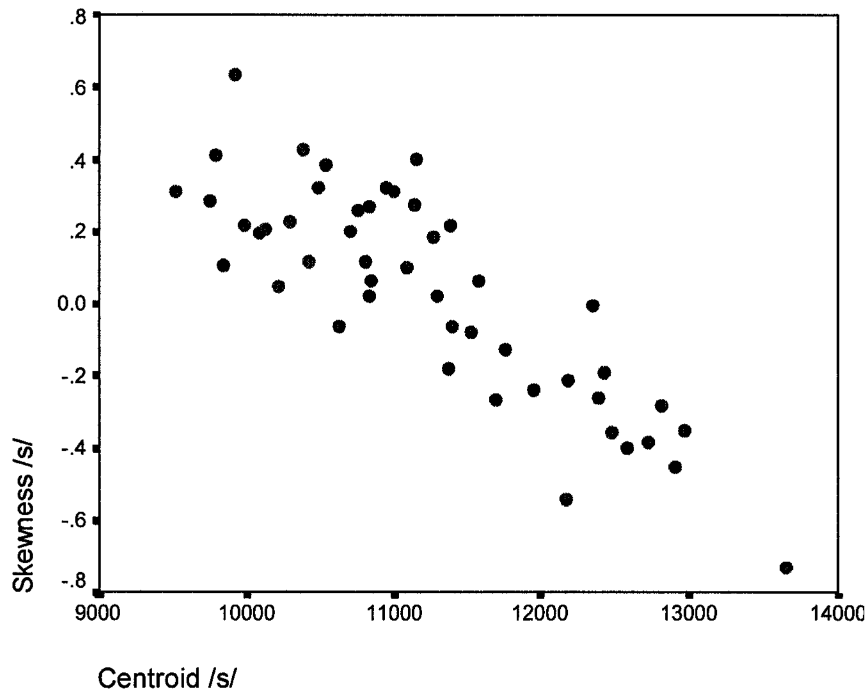
Acoustic Data for Target /s/ and /θ/ Productions (n=48)

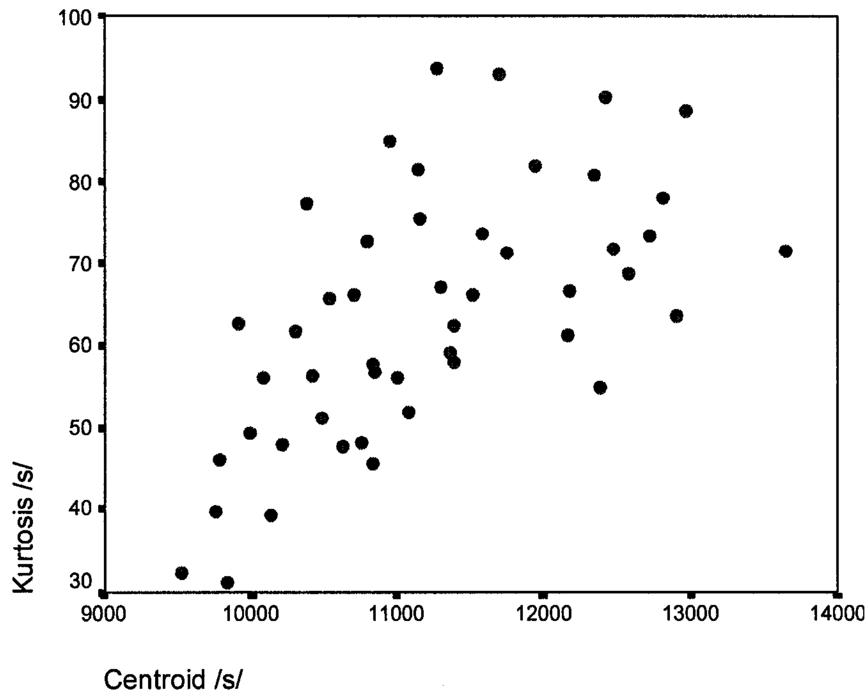
	M	*SD*	Minimum	Maximum
/s/ Centroid	11226.16	1011.28	9515.74	13655.63
/θ/ Centroid	12007.40	1144.96	9555.24	14368.59
/s/ Duration	214.44	69.40	139.63	524.73
/θ/ Duration	164.29	76.68	24.81	471.84
/s/ Skewness	0.03	0.29	-0.73	0.63
/θ/ Skewness	-0.31	0.26	-0.87	0.30
/s/ Kurtosis	63.73	15.28	31.24	93.85
/θ/ Kurtosis	58.74	16.23	28.07	90.47

Note. Centroid values are in Hertz (Hz); Duration values are in milliseconds (ms).

Figure 2

Mean /s/ skewness and kurtosis values in relation to mean /s/ centroid values (n = 48)





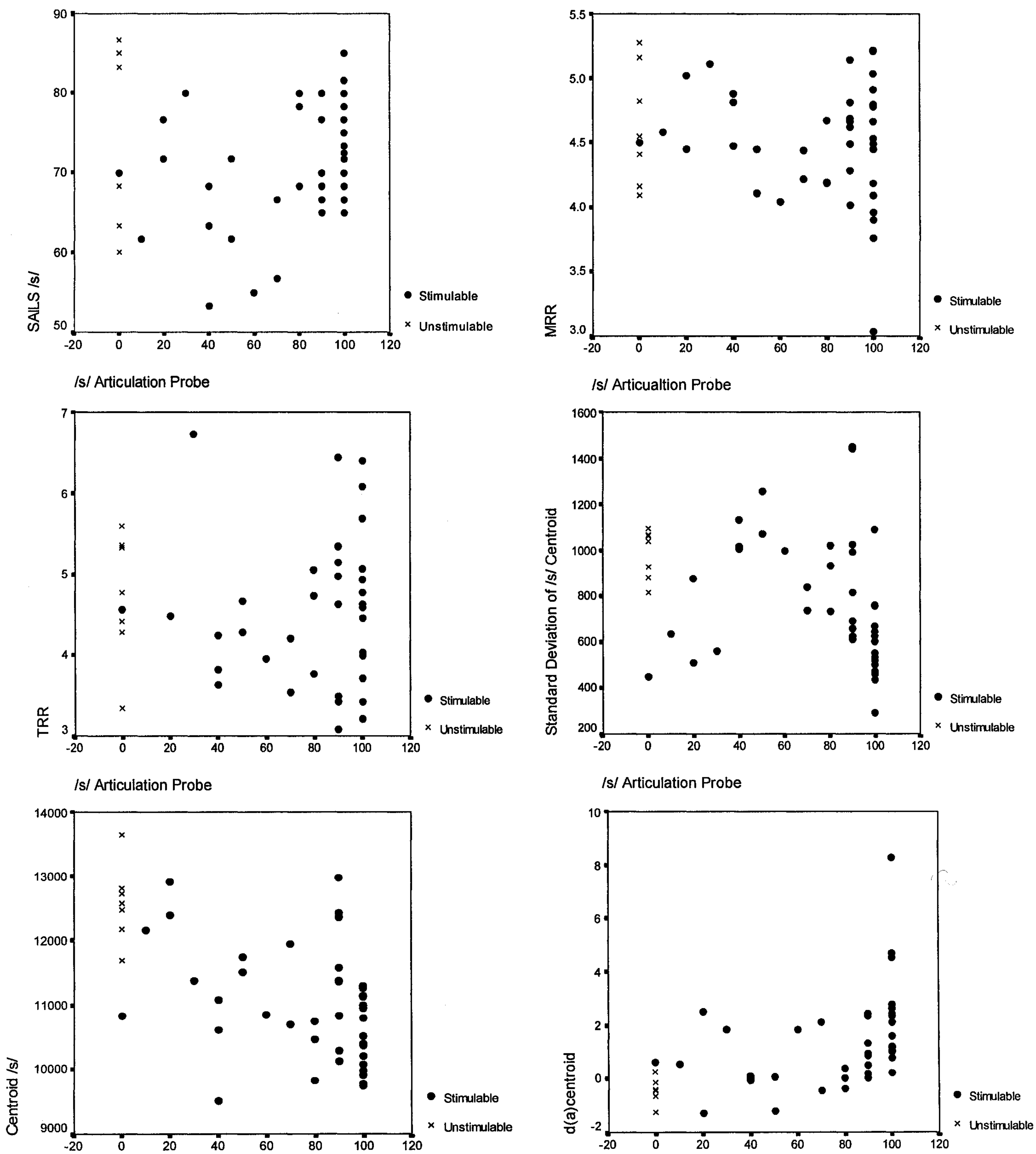
Correlations between Variables

Figure 3 shows the relationships between articulation accuracy and the following variables: SAILS performance, MRR and TRR scores, target /s/ centroid, SDcentroid (calculated from the standard deviations of each individual child's /s/ centroid values), and $d_{(a)}$centroid. Inspection of Figure 3 revealed three general patterns of performance. The first included the children who were unstimulable for /s/. These children showed a range of scores on SAILS, with some doing very poorly on the task and others managing to do quite well. Overall, they also showed low $d_{(a)}$centroids, high mean centroid values for /s/, and high standard deviations of their centroid values. The second group consisted of children whose perception scores were not very good and whose production was inconsistent as shown by their /s/ probe scores and in the standard deviations of their /s/ centroids. The third group showed good perception scores and good articulation accuracy. Their /s/ centroid values were low, as were the standard deviations of their /s/ centroids. In contrast with the current study which assessed perception of natural speech recorded from children and adults, Rvachew and Jamieson (1989) examined speech perception of carefully controlled synthetic stimuli in children with speech sound disorders. Their participants could also be divided into three groups: those who i) had poor perception and poor production; ii) good perception and poor production; or iii) good perception and good production. No children with poor speech perception were found to have good production. However, as can be seen from Figure 3, there were a few children in the current study with poor perception but good production. These children seemed to realize that some SAILS /s/ stimuli were correct and others incorrect, but were inconsistent in their perceptual judgments, responding at chance level.

For each plot in Figure 3, the participants were divided into two groups, those who were stimulable for /s/ (n = 41) and those who were unstimulable (n = 7). As can be seen from these graphs, there was quite a discrepancy in the pattern of results for the two groups. Based on past research examining the relationship between perception and production (e.g., Rvachew & Grawburg, in press), we would expect to see an increase in articulation accuracy as performance on SAILS increases. With the exception of a few outliers, this was seen for the group of stimulable children, but not for the unstimulable children. We would further expect to see articulation accuracy increase as $d_{(a)}$centroid increases. Again, this was seen for the group of stimulable children only. There was something very different about the performance of the unstimulable children relative to the stimulable children. In light of these different patterns of results, the previous finding that SAILS and stimulability are independent constructs (Rvachew et al., 1999), and the finding that stimulability does not reflect underlying phonological knowledge (Rvachew et al., 1999), it was decided that all further analyses would be based on the group of stimulable children only (n = 41). For the group of stimulable children, correlational analyses were carried out to examine the relationships among the variables in the current study. The correlation coefficients are shown in Table 4.

Figure 3

Articulation Accuracy in Relation to SAILS, MRR, TRR, standard deviation of /s/ centroid, /s/ centroid, and d(a)centroid



Correlations among Acoustic Measures

As can be seen from Table 4, SDcentroid was significantly correlated with the difference measure $d_{(a)}$centroid, indicating that as target /s/ centroid variability decreased, overlap among the distribution of target /s/ and target /θ/ centroids decreased. A significant negative relationship was also found between the $d_{(a)}$centroid and $d_{(a)}$duration.

Correlations with Acoustic-Phonetic Knowledge

Table 4 shows that SAILS was significantly and negatively correlated with SDcentroid and significantly and positively correlated with the percent correct /s/ productions. Children who demonstrated good perception skills produced less variability in their target /s/ centroid values and were more accurate in their /s/ productions. SAILS was also correlated with TRR. As performance on SAILS increased, children produced more syllables per second. No relationship was found between SAILS and SDduration, nor between SAILS and $d_{(a)}$duration.

Correlations with Articulatory-Phonetic Knowledge

Table 4 shows that the MRR and TRR tasks were significantly correlated with each other. However, neither task was significantly correlated with the measure of phonological knowledge, or with articulation accuracy.

Correlations with Underlying Phonological Knowledge

$D_{(a)}$centroid was significantly correlated with percent correct on the /s/ probe. As the overlap between target /s/ and target /θ/ centroid distributions decreased, the percentage of correct /s/ productions on the probe increased. $D_{(a)}$duration was not significantly correlated with /s/ probe performance.

Table 4

Bivariate Pearson Product-Moment Correlations Among Variables (n=41)

	Probe/s/	MRR	TRR	SAILS	SDcentroid	$d_{(a)}$centroid	SDduration	$d_{(a)}$duration
Probe /s/	1.00	-.146	.007	.306*	-.156	.368**	-.016	-.024
MRR		1.00	.426**	.240	.097	.007	-.026	-.058
TRR			1.00	.389**	.043	.034	-.197	-.012
SAILS				1.00	-.403**	.109	-.146	.214
SDcentroid					1.00	-.447**	.095	.252
$d_{(a)}$centroid						1.00	.243	-.396**
SDduration							1.00	-.227
$d_{(a)}$duration								1.00

Note. Probe /s/ = percent correct of /s/ productions; MRR = Monosyllabic Repetition Rate, syllables per second; TRR = Trisyllabic Repetition Rate, syllables per second; SAILS = Speech Assessment and Interactive Learning System, percent correct; SDcentroid = calculated from the standard deviation of each child's /s/ centroid values; $d_{(a)}$centroid = degree of separation between /s/ and /θ/ centroid distributions; SDduration = calculated from the standard deviation of each child's /s/ durations; $d_{(a)}$duration = degree of separation between /s/ and /θ/ duration distributions.

**The correlation is significant at the .01 level.
*The correlation is significant at the .05 level.

Contributions to Accurate Articulation

In order to further examine the relationship between the predictor variables and the outcome measure, hierarchical multiple regression analyses were carried out using articulatory-phonetic ability (MRR and TRR), acoustic-phonetic knowledge (SAILS), and underlying knowledge of the /s/-/θ/ contrast ($d_{(a)}$centroid) as independent variables, and /s/ articulation accuracy as the dependent variable. $D_{(a)}$duration was not included in this analyses as it was not found to significantly correlate with the outcome measure, nor with the predictor variables. The ordering of the variables was determined *a priori* on the basis of what is known about phonological development. Although all three areas of knowledge develop and mature as children gain experience with their native language, significant development of perceptual and articulatory knowledge occurs during infancy, before the emergence of the child's first words. As a result, the phonetic variables were entered into the analysis before the phonological variable. Together, the independent variables explained 25.7% of the variance in articulation accuracy. However, only the SAILS measure and $d_{(a)}$centroid were found to contribute significantly to the regression formula. Performance on the MRR and TRR tasks was not found to explain any unique variance in articulation accuracy. SAILS explained 11.9% of the variance in articulation accuracy, while $d_{(a)}$centroid explained 11.0%. Regression coefficients, r^2, change in r^2, and statistics are shown in Table 5.

The finding that SAILS was not significantly correlated with $d_{(a)}$centroid was surprising given the significant correlations found between SAILS and

Table 5

Results of Multiple Hierarchical Regression Analysis Conducted to Identify Predictive Relationships Between the Independent Variables and Articulation Accuracy (n=41)

Predictor	r	r^2	Change in r^2	F Change	P
MRR and TRR	.164	.027	.027	.485	.620
SAILS	.383	.146	.119	4.756	.036
$d_{(a)}$centroid	.507	.257	.110	4.897	.034

SDcentroid and between SDcentroid and $d_{(a)}$centroid. In order to further examine these relationships, independent *t*-tests were used to divide the children into clusters based on the acoustic cues they used to signal the distinction between their target /s/ and /θ/ productions.

Cluster Analysis

The results of the *t*-tests revealed that the children fell into four clusters. The following is a brief description of each cluster.

Description of Clusters

Cluster 1. Each child in cluster 1 produced a significant difference between mean centroid values for their target /s/ and /θ/ productions, as well as a significant difference between mean duration values for their target /s/ and /θ/ productions. Children in this group utilized both centroid and duration to distinguish their productions. Eleven children fell into this cluster. Box-plots comparing target /s/ and /θ/ centroid and target /s/ and /θ/ duration values for children in cluster 1 are shown in Figure 4.

Cluster 2. Each child in cluster 2 produced a significant difference between mean centroid values for their target /s/ and /θ/ productions, but did not produce a significant difference between mean duration values for their target /s/ and /θ/ productions. Children in this group utilized centroid only to distinguish their productions. Thirteen children fell into this cluster. Box-plots comparing target /s/ and /θ/ centroid and target /s/ and /θ/ duration values for children in cluster 2 are shown in Figure 5.

Cluster 3. Each child in cluster 3 produced a significant difference between mean duration values for their target /s/ and /θ/, but did not produce a significant difference between mean centroid values for their target /s/ and /θ/. Children in this group utilized duration only to distinguish their productions. Eleven children fell into this cluster. Box-plots comparing target /s/ and /θ/ centroid and target /s/ and /θ/ duration values for children in cluster 3 are shown in Figure 6.

Cluster 4. Children in cluster 4 did not use either cue to distinguish their productions of /s/ and /θ/. They did not produce a significant difference between their mean centroid values, nor did they produce a significant difference between their mean duration values. Six children fell into this cluster. Box-plots comparing target /s/ and /θ/ centroid and target /s/ and /θ/ duration values for children in cluster 4 are shown in Figure 7.

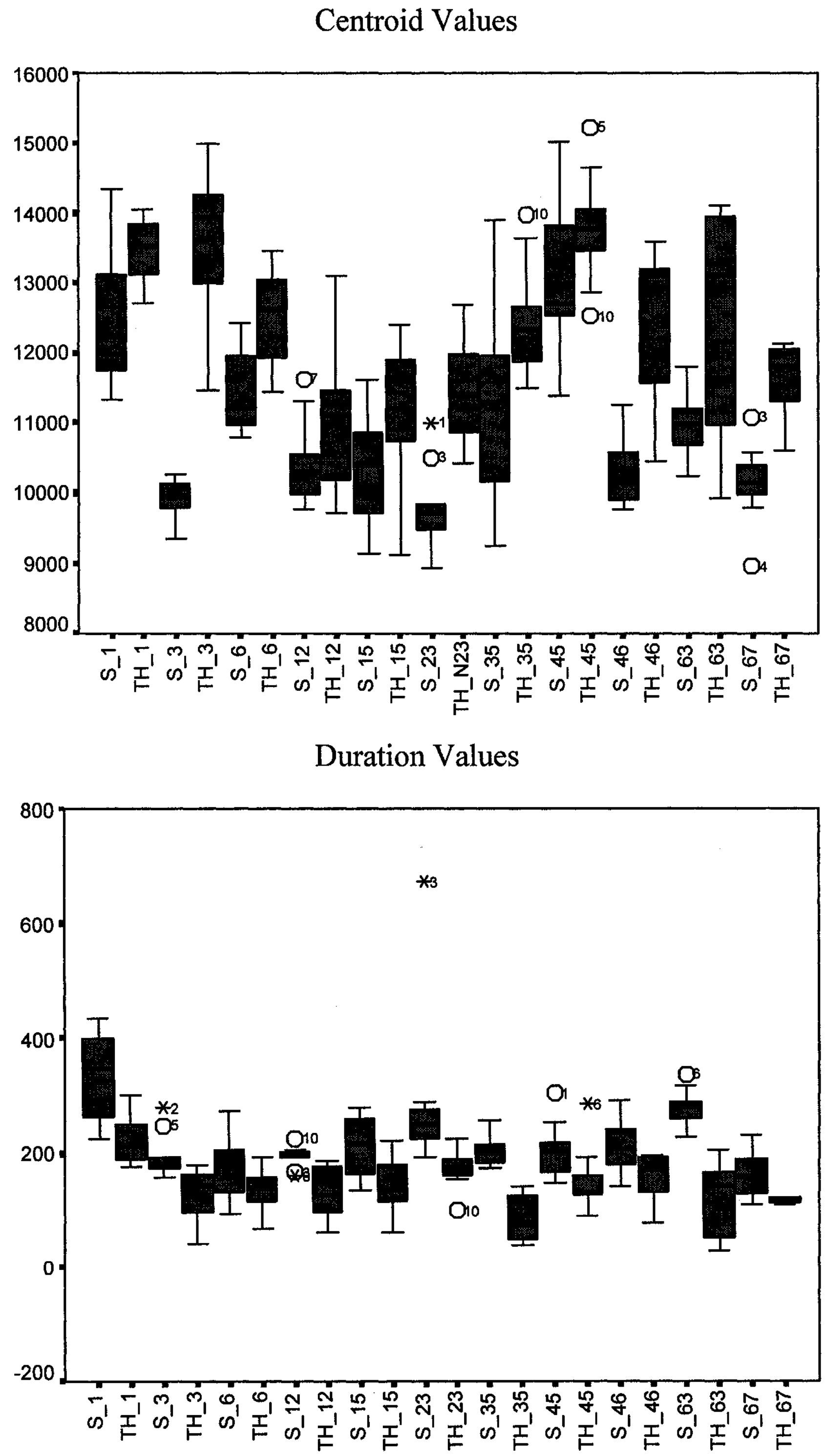
Differences among Clusters.

Table 6 shows the results of a one-way ANOVA used to examine differences between the four clusters. Table 6 also shows the results of Fisher's Least Significant Difference (LSD) post hoc multiple comparisons test which was used to further evaluate the differences between the clusters.

Acoustic-Phonetic Knowledge. The results of the ANOVA indicated that there was a significant difference in SAILS performance between the four clusters. The post hoc analysis revealed that cluster 1 had the best SAILS performance, and this was significantly better than the performance of cluster 2

Figure 4

Target /s/ and /θ/ centroid and duration values for each participant in cluster 1



Note. S1 = /s/ centroid for participant 1; TH1 = /θ/ centroid for participant 1.

Figure 5

Target /s/ and /θ/ centroid and duration values for each participant in cluster 2

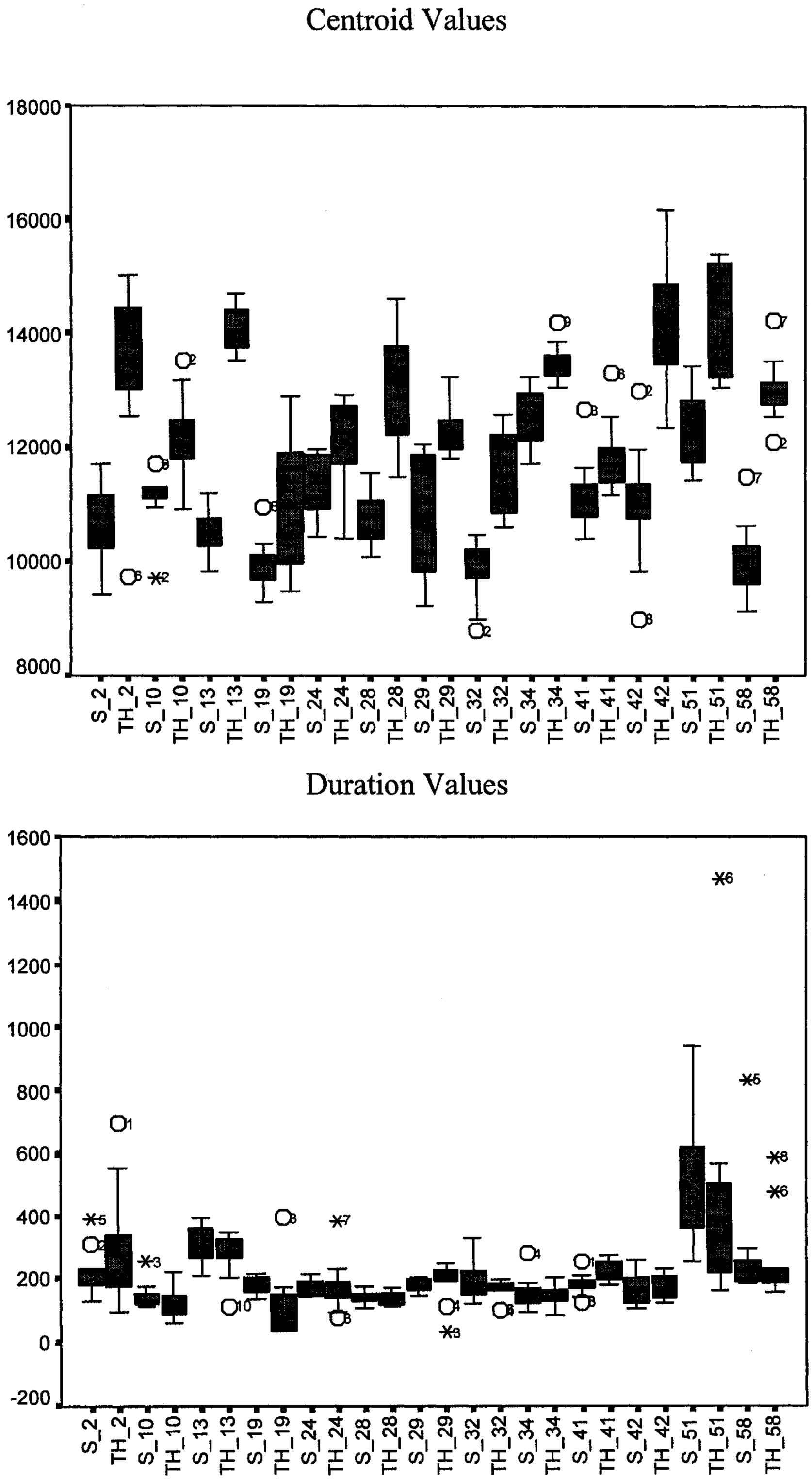


Figure 6

Target /s/ and /θ/ centroid and duration values for each participant in cluster 3

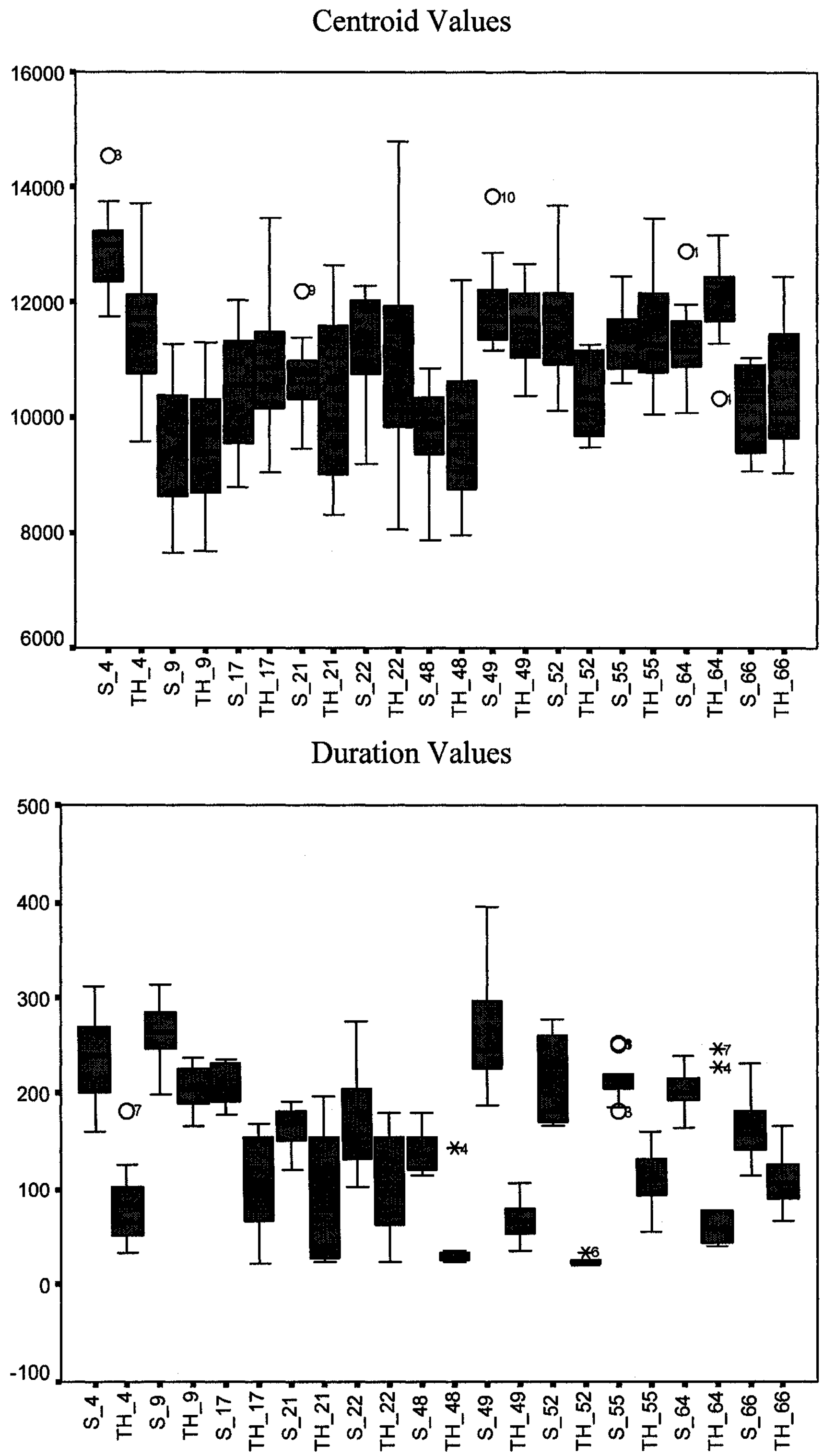
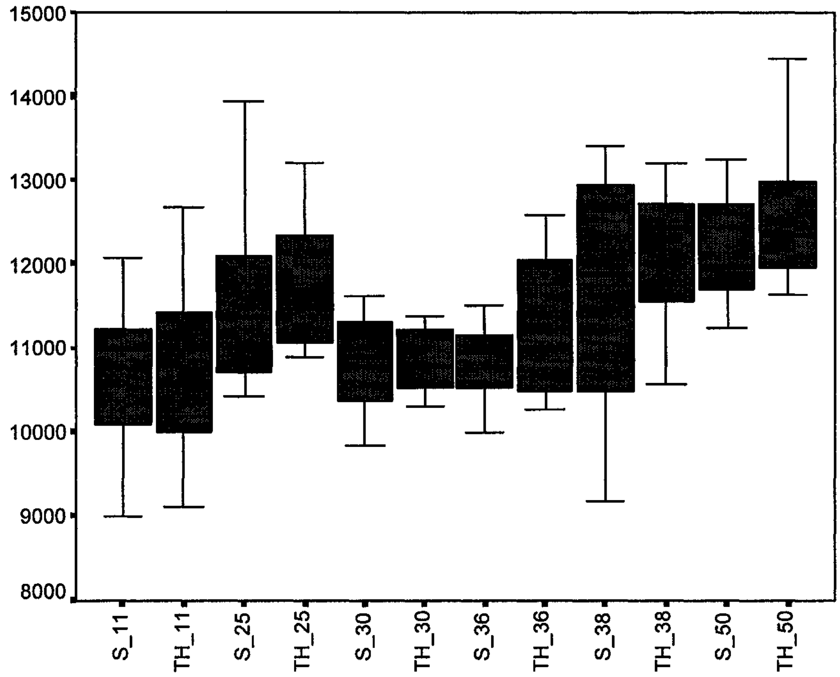


Figure 7

Target /s/ and /θ/ centroid and duration values for each participant in cluster 4

Centroid Values



Duration Values

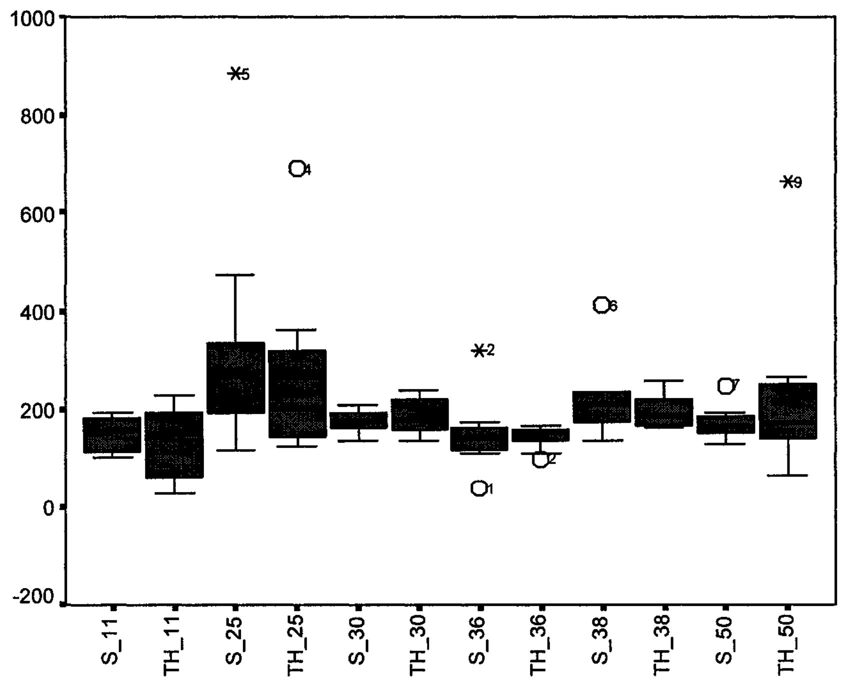


Table 6

Mean (Standard Deviation) Results of the Analysis of Variance and LSD Post Hoc Multiple Comparisons Test of Between Cluster Differences

	Cluster 1 (n=11)	Cluster 2 (n=13)	Cluster 3 (n=11)	Cluster 4 (n=6)	*F*	*p*	LSD
Probe /s/	89.09(20.23)	87.69(24.21)	68.18(26.77)	46.67(38.30)	4.559	.008	1,2>4; 3=1,2,4
$d_{(a)}$centroid	1.77(1.12)	2.67(1.94)	-0.15(0.63)	0.31(0.27)	11.118	.000	1,2>3,4
$d_{(a)}$duration	1.67(0.85)	0.12(0.54)	2.73(1.34)	0.05(0.35)	21.558	.000	3>1>2,4
SAILS	75.76(6.07)	68.21(6.54)	70.53(7.84)	67.22(5.74)	3.228	.033	1>2,4; 3=1,2,4
MRR	4.66(0.37)	4.29(0.54)	4.50(0.43)	4.64(0.17)	1.743	.175	n/a
TRR	4.68(1.27)	4.29(0.77)	4.49(0.89)	4.76(0.42)	.461	.711	n/a

and cluster 4, but not significantly better than cluster 3. The SAILS performance of cluster 3 was the second highest but this was not significant. Figure 8 shows a break down of each cluster's performance on each of the three levels of SAILS. While speech perception performance tended to be better for level 1 for all clusters, there was a clear difference between the performance of cluster 1 and the remaining clusters on the more difficult levels 2 and 3.

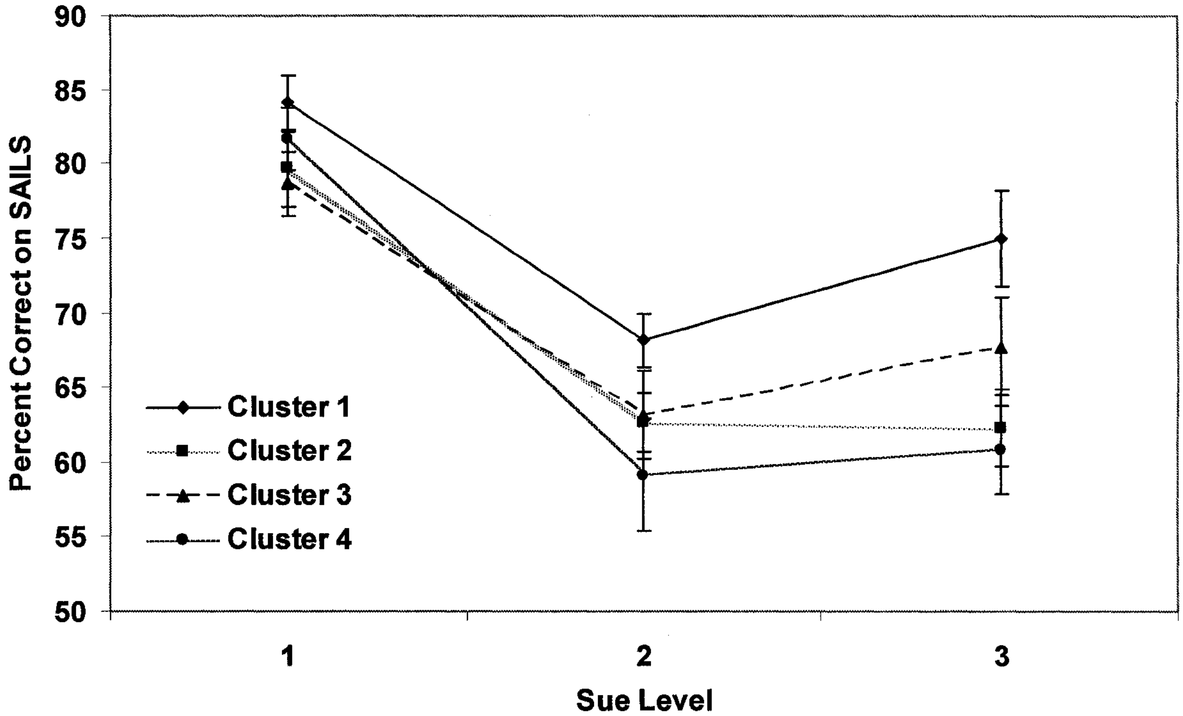
Articulatory-Phonetic Knowledge. The results of the ANOVA revealed that the four clusters did not differ significantly on the MRR and TRR tasks.

Phonological Knowledge of /s/-/θ/ Contrast. The results of the ANOVA indicated that there were significant differences between the clusters on $d_{(a)}$centroid and $d_{(a)}$duration. The post hoc analyses revealed, as expected given the criteria used to form the clusters, that clusters 1 and 2 had significantly larger $d_{(a)}$centroids than clusters 3 and 4. Similarly, clusters 1 and 3 were found to have significantly larger $d_{(a)}$durations than clusters 2 and 4.

Articulation Accuracy. The results of the ANOVA also revealed significant differences between the four clusters with respect to the main outcome measure, articulation accuracy. Post hoc analyses revealed that children in clusters 1 and 2 scored significantly higher on the single word /s/ probe than did children in cluster 4. They also scored higher than the children in cluster 3 but this difference was not significant.

Figure 8

Performance of the Four Clusters on Each Level of SAILS



Discussion

The purpose of this study was to examine children's acoustic-phonetic, articulatory-phonetic, and phonological knowledge in order to evaluate the contributing factors to accurate articulation. Performance on the SAILS measure of speech perception and a measure of children's underlying phonological knowledge of the /s/-/θ/ contrast (i.e., $d_{(a)}$centroid) were each found to explain significant amounts of the variance in articulation accuracy. MRR and TRR scores did not explain a significant amount of variance in articulation accuracy. Stimulability emerged as a limiting factor separating participants into two groups with very different patterns of performance on the independent variables.

Acoustic-Phonetic Knowledge

A direct link between acoustic-phonetic knowledge of /s/ and articulation accuracy of /s/ was observed for the group of children who were stimulable for /s/. Performance on SAILS explained 11.9% of the variance in articulation accuracy. These results support the *Speech Perception Hypothesis* and are consistent with research emphasizing the role of speech perception in the development of articulation accuracy. The current findings, along with previous research examining concurrent relationships between speech perception and articulation accuracy (e.g., Rvachew & Grawburg, in press; Rvachew & Jamieson, 1989), longitudinal relationships between speech perception and articulation accuracy (e.g., Rvachew, in press), and the effectiveness of speech perception training on articulation accuracy (e.g., Rvachew et al., 2004), support the hypothesis that speech perception is causally related to the development of articulation accuracy.

Perkell et al. (2004a, 2004b) hypothesize that this relationship between perception and production begins during language learning. Children who are better able to perceive fine acoustic-phonetic details learn auditory goal regions that are smaller and spaced further apart, resulting in productions which are more distinct and intelligible. This hypothesis corresponds with Rvachew et al.'s (2004) suggestion that speech perception training leads to improvements in articulation accuracy because it provides children with more accurate acoustic representations of sounds and thus with more accurate targets for production. According to these hypotheses, children with good acoustic-phonetic knowledge have accurate underlying representations and therefore appropriate targets for production. However, a direct linear relationship was not found in the current study between SAILS and the measure of underlying phonological knowledge (i.e., $d_{(a)}$centroid). On the other hand, inspection of Figure 8 revealed that a relationship did in fact exist between acoustic-phonetic and phonological knowledge when each cluster was examined separately. All four clusters generally scored better on the first level of SAILS than on levels 2 and 3. Of interest is the performance of the clusters on the more difficult levels 2 and 3. It can be seen from Figure 8 that cluster 1 was performing significantly better than the other clusters on these levels. Children who distinguished their own target /s/ and /θ/ productions using both centroid and duration performed better on levels 2 and 3 than children who used only centroid, children who used only duration, and children who used neither cue. Children who possessed greater productive phonological knowledge of the contrast were those who were better able to identify correct and incorrect /s/ productions on the more difficult SAILS levels.

Although a direct linear relationship was found between SAILS and articulation accuracy, it was not as strong as would be expected given the findings of Rvachew and Grawburg (in press). In addition, although examination of Figure 8 revealed a relationship between perception and phonological knowledge, a significant correlation between the two variables was not found. Possible explanations for these findings will now be discussed.

Firstly, SAILS might not have been the best measure of acoustic-phonetic knowledge for this study. Listeners often have more than one cue available to them and may base perceptual judgments on different cues at different times (Newman, 2003). As stated by Rvachew and Jamieson (1989), one cannot know which acoustic cues children are using to make perceptual judgments unless the cues are manipulated systematically and orthogonally. Furthermore, one should not expect to find correlations between speech perception and production unless the cues being measured during production tasks are related to the cues used by the listener during perception tasks (Newman, 2003).

Unfortunately, acoustic cues were not carefully controlled in SAILS. As a result, it was not possible to know with certainty which cues the children were attending to. However, as can be seen from Table 6, the children who achieved reasonable perception performance were those who used duration to signal the distinction between their productions of /s/ and /θ/ (i.e., the children in clusters 1 and 3). This led to the hypothesis that participants might have used duration to identify tokens of /s/ in SAILS. If true, this would explain the lack of a direct linear relationship between SAILS and $d_{(a)}$centroid as the cue being used in perception was not the same as the cue signaling the contrast between /s/ and /θ/. Acoustic analysis of the SAILS stimuli revealed acoustic differences between correct and incorrect /s/ stimuli. However, as can be seen from Table B1 of Appendix B, the same acoustic cues were not used on all three levels of SAILS and duration was only important for distinguishing target and foil stimuli on one of the three levels. Appendix B also presents the results of secondary analyses used to examine possible relationships between the cues differentiating stimuli on each level of SAILS and the cues used by the stimulable participants to differentiate their own target /s/ and /θ/ productions. It was hypothesized that relationships would emerge between perceptual performance on the different levels of SAILS and production if the cues used by the children in their own speech production were the same as those used to differentiate correct and incorrect stimuli on each SAILS level. As can be seen from Tables B2 and B3, none of the analyses supported this hypothesis.

It is also possible that the children were attending to some other aspect of the SAILS stimuli. Perhaps they were basing their perceptual judgments on dynamic cues (i.e., formant transitions) that link the fricative to the vowel within the syllable (Nittrouer, 1992). Performance may also have been affected by the fact that children's perceptual strategies are not as flexible as adults' (Hazan & Barrett, 2000). Children scored the highest on the SAILS level which used the most cues to signal the difference between correct and incorrect /s/ productions (see Figure 1), indicating that they performed better when more cues were available (Hazan & Barret, 2000). In order to more adequately examine the relationship between perception and production in children, future research should systematically and orthogonally control the spectral, temporal, and dynamic cues signaling the fricative contrast.

Articulatory-Phonetic Knowledge

MRR and TRR tasks were used in the current study in an attempt to obtain a pure measure of articulatory ability. These tasks provide an indication of the coordinative ability of the lips and tongue, the child's ability to precisely manipulate and control their articulators (Thoonen et al., 1996). Edwards et al. (1999) have suggested that the speech errors of children with speech sound disorders may be at least partly due to deficits at the level of articulatory-phonetic knowledge. Contrary to the *Articulation Hypothesis,* articulatory-phonetic ability, as measured by MRR and TRR tasks, did not explain any significant portion of the variance in accurate articulation. This was surprising given previous findings that children with speech sound disorders have difficulty with maximum repetition tasks (e.g., McNutt, 1977; Wolk et al., 1993).

This lack of a direct linear relationship between the two maximum repetition tasks and articulation accuracy might be the consequence of participant characteristics or might suggest that these tasks were not the best tools for the current study. As a group, children scored within normal limits for their age on the MRR and TRR tasks (Robbins & Klee, 1987). A different pattern of results might have emerged had there been a larger range of scores on these tasks. In addition, these tasks were used by Thoonen et al. (1996) for differential diagnosis of childhood apraxia of speech and dysarthria. The participants in the current study were all children who scored at or above the 16th percentile on the GFTA-2 and presented with no obvious oral-motor difficulties. In the case of children who did score below the average expected for their age, this was not necessarily an indication of poor motor skill. For some children, there appeared to be a speed-accuracy trade off, especially for the TRR task. These children appeared more concerned with the accuracy of their syllable repetitions (e.g., "If I go faster, I won't say it right"), causing them to slow down to ensure accurate repetitions. This observation is interesting given Yaruss and Logan's (2002) suggestion that accuracy and fluency on DDK tasks may provide information regarding speech development that is more closely related to oral motor development than is rate.

Whether or not a child is stimulable for a sound has the potential to provide information about articulatory-phonetic knowledge. The children in the current study were divided into two groups: those who were stimulable for /s/ and those who were not. Because stimulability is a dichotomous variable, it was not possible to enter it into the multiple hierarchical regression analysis. However, stimulability was an important variable in the current study as it emerged as a limiting factor. A very different pattern of results emerged for the children who were stimulable for /s/ compared to the children who were not. However, failure to stimulate a child to produce a correct /s/ does not necessarily reflect problems with the child's articulatory system itself. Kwiatkowski and Shriberg's (1993) two factor theory describes stimulability as involving components of both *capability* and *focus*. Capability consists of the child's comprehension and production phonology, as well as any risk factors facing the child (e.g., problems with the structure or functioning of speech and hearing mechanisms). Focus includes the child's motivation and effort to change their speech productions. As a result, a child who is unstimulable may lack the capability needed to produce the sound, may lack the motivation needed to change their production, or may lack both the capability and the focus (Kwiatkowski & Shriberg, 1993). The current study did not include a measure of focus. It was therefore not possible to determine if lack of stimulability in certain participants indeed indicated a problem with the articulatory system.

Perhaps the current research did not select appropriate tools for measuring articulatory-phonetic knowledge. In order to assess articulatory-phonetic knowledge, a measure needs to be purely articulatory, independent of acoustic-phonetic and phonological knowledge. It was believed that the MRR and TRR tasks provided such a tool. However, correlational analyses revealed that the TRR was not independent of acoustic-phonetic knowledge. Furthermore, the MRR and TRR tasks represented general measures of articulatory/motor ability. As a result, performance on these tasks may have been independent of whatever it was that allowed some children to produce the precise articulatory gestures required to produce an accurate /s/ while other children could not. A better measure of articulatory ability might therefore have consisted of a tool which provided information regarding the child's ability to control and coordinate their articulatory gestures while producing /s/. Stimulability may therefore have been a slightly better measure as it was specific to children's ability to imitate /s/ and is independent of speech perception skills (Rvachew et al., 1999). However, the issue of capability versus focus suggests that it may not be a pure measure of articulatory skill. Maybe a tool such as EPG would have been a better measure of articulatory-phonetic knowledge for the current study. Production of /s/, as already discussed, requires precisely controlled movements of the tongue. EPG has been employed to directly measure tongue tip/blade and tongue body activity during the production of lingual consonants such as /s/ (Gibbon, 1999). For example, idiosyncratic EPG patterns were observed for the dentalized fricatives and affricates produced by one child in Gibbon et al.'s (1995) examination of the articulatory characteristics of fricative and affricate distortions. However, EPG has also been used to reveal the presence of imperceptible covert contrasts in children with speech sound disorders (Gibbon, 1999) and therefore may not be independent of phonological knowledge.

Phonological Knowledge

Phonological knowledge of the /s/-/θ/ contrast was assessed by calculating $d_{(a)}$ for children's centroid and duration values. $D_{(a)}$ values which reflect distinct distributions for target /s/ and /θ/ suggest the child possesses at least some underlying knowledge of the /s/-/θ/ contrast, some knowledge of the distinctive feature [+distributed]. Large $d_{(a)}$ values indicate less overlap between /s/ and /θ/ distributions as they represent greater distance between the means for each distribution, as well as values that cluster more around their respective means. The results of the current study found a direct link between phonological knowledge of /s/ and articulation accuracy for the group of stimulable children. That is, underlying phonological knowledge, as measured by $d_{(a)}$centroid, explained a small but significant portion (11%) of the variance in accurate articulation of /s/. The children who were more accurate at producing /s/ were those who showed less overlap between their target /s/ and /θ/ centroid distributions. This finding is consistent with Newman et al.'s (2001) conclusion that talkers who have phoneme categories which are very distinct from each other as well as highly internally consistent have more consistent productions and are more intelligible to listeners. This relationship between $d_{(a)}$centroid and articulation accuracy highlights the importance of a more abstract level of representation to accurate articulation.

The results of the cluster analysis revealed that the children with the most accurate articulation on the single word probe were those who used centroid to signal the distinction between their productions of target /s/ and /θ/ (i.e., the children in clusters 1 and 2). This finding might explain the strong correlation between articulation accuracy and $d_{(a)}$centroid. It would seem the cue important for both articulation accuracy and phonological knowledge was centroid.

Regardless of the accuracy of children's /s/ productions, examination of the four clusters revealed that discontinuities between phonological knowledge and phonetic knowledge did exist for some children. For example, of the children in cluster 1, ten scored 90% or 100% on the articulation probe, while one scored 30%. This last child's /s/ productions were dentalized but were distinguished acoustically from /θ/ using both centroid and duration. This child was producing a covert contrast, demonstrating knowledge of the contrast that was not evident from the perceptual analysis alone. Of the children in cluster 4, four children scored between 0% and 50% on the articulation probe, while two scored 90%. These two children were maintaining a phonetic contrast between /s/ and /θ/ that was perceptible to listeners. However, they were using neither centroid nor duration to signal this distinction. As can be seen from these examples, instrumental analysis revealed more about the children's phonological knowledge than perceptual analysis alone.

Implications for Clinical Practice

The current findings demonstrate that both phonetic skills and phonological knowledge are important to the development of articulation accuracy. Specifically, acoustic-phonetic and phonological knowledge of /s/ contributed significantly to accurate articulation of /s/. Although a direct linear relationship was not found between the maximum repetition tasks and articulation accuracy, stimulability did have an impact on children's performance. These results suggest that both phonetic and phonological knowledge might also be implicated in the errors of children with speech sound disorders. As a result, it is important that practicing clinicians consider both phonetic and phonological knowledge during the assessment and treatment of children with speech sound disorders.

Limitations and Directions for Future Research

Speech Perception Measure

SAILS was not the best measure of speech perception for the current study. As already discussed, the SAILS stimuli were not carefully controlled, making it impossible to determine with certainty which cues accounted for the children's responses. This shortcoming of SAILS may help explain the lack of certain expected relationships and the weakness of others. Future research examining such relationships should use synthetic speech stimuli in perception tasks to permit careful manipulation of stimulus cues.

Articulatory-Phonetic Measures

Future research needs to identify a measure of articulatory-phonetic knowledge which provides information regarding the articulatory characteristics specific to the target sound being investigated, but which is also independent of acoustic-phonetic and phonological knowledge.

Target Phonemes

While the SAILS stimuli used to assess acoustic-phonetic knowledge of /s/ contrasted correct productions with many different misarticulations of /s/, the production task only examined the /s/-/θ/ contrast. Future research might limit the perception stimuli to only those targeting the contrast assessed during production.

Furthermore, it is possible that /s/ was not the best sound to target in the current study, specifically because it is the least marked of the English fricatives (Chomsky & Halle, 1968). Future research might target a different phoneme that is also commonly misarticulated by this age group.

Participants

Sample Size. Although a large number of children were recruited for the current study, the loss of certain participants and the exclusion of others resulted in a smaller final sample size. This was especially evident in the cluster analysis. Statistical analysis of the relationships among variables within each cluster was not possible given their small size. A larger sample size in future research might reveal some interesting relationships between the dependent and independent variables within each cluster of children.

Participant Characteristics. The current study only included children with typically developing speech. Previous research has examined the acoustic cues used by children with speech sound disorders. Forrest et al.'s (1990) examination of the acoustic characteristics of /k/ and /t/ revealed that children with speech sound disorders sometimes used different or fewer cues than children with typically developing speech when producing these sounds: "perceptually correct productions by a phonologically disordered speaker may be different from the productions of a child who never demonstrated misarticulations" (Forrest et al., 1990, p.337). Miccio (1995) also found in her study that some of the children with speech sound disorders used different cues than their typically developing peers to signal fricative contrasts, both before treatment and as new sounds were being introduced into their phonetic inventory. Including children with speech sound disorders in future research would extend the results of the current study by furthering our understanding of the relationships between acoustic-phonetic knowledge, articulatory-phonetic knowledge, underlying phonological knowledge, and articulation accuracy in this population.

Testing Environment

When recording and analyzing speech, and when assessing speech perception skills, a quiet environment is important. Optimally, such assessments would take place in an acoustically treated area such as a sound-attenuated booth. In the present investigation, assessments were carried out either in the participant's daycare/school or in the house of the author's supervisor. Although all efforts were made to ensure a quiet environment, this was not always possible. Past research has shown that children have a harder time than adults perceiving speech degraded by noise. Levels of noise which would have minimal effects on adult speech perception performance can have a considerable effect on the speech perception of a child (e.g., Elliott, 1979; Mills, 1975). It is not possible to know for sure whether or how much background noise affected the results on the perception task in the current study. Future research would benefit from conducting similar assessments in a sound booth.

Concurrent versus Longitudinal Relationships

The relationship between speech perception and later articulation accuracy seems to be stronger than when the two are assessed concurrently (Rvachew, in press). The present investigation examined these variables concurrently. Future research examining the variables and relationships from the current investigation might expand on the present findings by looking at the variables longitudinally.

Conclusion

This study found that acoustic-phonetic knowledge and phonological knowledge each explained a significant amount of the variance in articulation accuracy. The findings highlight the role of speech perception in the development of accurate articulation and thus lend support to previous research advocating the use of speech perception training during the remediation of speech sound errors. In addition to accurate and detailed acoustic representations for words, a more abstract level of representation was also found to be important to the development of articulation accuracy. The present results thus underline the importance of including instrumental analysis when evaluating phonology in children. Although a direct linear relationship was not found between the maximum repetition rates and articulation accuracy, stimulability did emerge as an important limiting factor. Replication of the current findings with children with speech sound disorders is needed in order to better understand the nature of the relationships between acoustic-phonetic knowledge, articulatory-phonetic knowledge, phonological knowledge, and articulation accuracy in this population of children.

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Appendix A

Individual Test Results and Acoustic Data

Table A1

Individual Participant Results for the Group of Stimulable and Unstimulable Children (n = 48)

Participant	Probe /s/ Score	MRR	TRR	SAILS	$d_{(a)}$centroid	$d_{(a)}$duration
001	90	4.66	-	80.00	1.35	1.63
002	70	4.44	4.20	56.67	2.13	-0.42
003	100	4.53	5.69	81.67	4.55	1.54
004	20	4.45	-	71.67	-1.27	3.18
006	30	5.11	6.74	80.00	1.86	0.86
007	0	4.09	4.78	86.67	-0.15	0.00
009	40	4.47	3.64	53.33	0.04	2.04
010	100	3.03	3.42	70.00	1.63	0.52
011	40	4.88	4.24	68.33	0.10	0.35
012	100	4.18	3.72	75.00	0.79	1.78
013	100	4.78	4.59	71.67	8.28	0.48
015	90	4.28	3.49	68.33	0.90	1.29
017	80	4.67	4.74	78.33	0.40	2.53
019	100	4.45	3.99	70.00	1.18	0.76
021	80	4.19	3.77	68.33	-0.37	1.30
022	40	4.81	3.82	63.33	-0.06	1.33
023	100	5.04	4.77	85.00	2.47	1.11

024	100	4.80	6.08	68.33	1.02	-0.13
025	50	4.45	4.67	61.67	0.06	0.27
028	100	3.90	3.99	70.00	2.39	0.34
029	60	4.04	3.95	55.00	1.86	-0.25
030	90	4.62	5.35	76.67	0.03	-0.34
032	100	3.76	4.03	73.33	2.66	0.72
033	0	4.41	3.35	68.33	0.26	0.06
034	20	5.02	4.49	76.67	2.53	0.48
035	90	4.69	6.45	68.33	0.95	3.54
036	0	4.50	4.56	70.00	0.62	0.06
038	90	4.81	4.97	65.00	0.52	0.37
039	0	4.16	5.33	85.00	-0.64	1.13
041	100	4.66	5.07	76.67	1.07	-1.19
042	100	4.49	4.94	66.67	2.80	-0.02
045	90	4.66	3.43	70.00	0.85	0.99
046	100	4.09	4.63	78.33	2.14	1.21
047	0	4.82	4.42	83.33	-0.40	-0.87
048	80	4.18	5.05	80.00	0.02	2.99
049	70	4.22	3.54	66.67	-0.45	4.29
050	10	4.58	-	61.67	0.53	-0.42
051	90	4.49	3.08	66.67	2.47	0.17
052	50	4.11	4.29	71.67	-1.20	5.61
055	90	4.02	5.15	70.00	0.17	3.38

058	100	3.96	3.99	65.00	4.72	0.11
062	0	5.16	5.36	60.00	-0.47	0.90
063	100	4.91	3.21	78.33	1.23	3.00
064	100	5.22	4.46	72.50	0.78	1.78
065	0	4.55	4.29	70.00	0.27	0.71
066	100	5.21	6.41	80.00	0.24	1.62
067	90	5.14	4.63	68.33	2.38	1.37
068	0	5.28	5.60	63.33	-1.23	0.04

Note. Dashes indicate that TRR data were missing for these children because they were unable to produce a correct trisyllabic sequence.

Table A2

Individual Acoustic Data for Stimulable and Unstimulable Children (n = 48)

Participant		Centroid		Duration		Skewness		Kurtosis	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
001									
	/s/	12424.37	994.67	325.05	78.79	-0.19	0.40	90.20	13.91
	/θ/	13468.38	449.60	224.04	38.35	-0.66	0.24	68.47	23.71
002									
	/s/	10697.41	739.21	230.96	73.98	0.20	0.31	66.07	14.850
	/θ/	13336.20	1591.16	296.67	206.44	-0.59	0.32	76.27	27.63
003									
	/s/	9908.95	290.60	195.79	38.08	0.63	0.10	62.60	6.26
	/θ/	13598.26	1108.67	129.76	47.21	-0.62	0.19	71.40	19.43
004									
	/s/	12909.53	875.87	236.27	47.80	-0.45	0.25	63.56	17.52
	/θ/	11554.16	1229.18	82.33	49.02	-0.46	0.22	42.19	21.44
006									
	/s/	11391.96	561.35	179.34	54.52	-0.06	0.23	62.47	12.13
	/θ/	12524.52	650.00	139.76	35.47	-0.43	0.26	72.46	14.70
007									
	/s/	11696.82	1061.17	251.79	102.99	-0.27	0.20	92.99	33.46
	/θ/	11529.01	1169.98	251.68	221.78	-0.24	0.37	56.03	11.97
009									
	/s/	9515.74	1132.74	262.63	32.47	0.31	0.39	32.34	5.44
	/θ/	9555.24	1112.83	204.46	23.78	0.30	0.32	33.06	6.39
010									
	/s/	11143.09	554.25	147.51	42.56	0.28	0.17	81.42	14.73
	/θ/	12207.08	740.41	124.75	44.23	-0.20	0.30	53.27	5.78
011									
	/s/	10623.13	1017.88	153.80	35.23	-0.06	0.33	47.81	12.69
	/θ/	10726.18	1034.54	133.91	72.60	-0.23	0.29	46.21	13.71
012									
	/s/	10414.62	605.02	194.94	18.56	0.12	0.24	56.52	8.87
	/θ/	11096.70	1069.20	132.95	45.58	-0.14	0.26	53.09	11.38
013									
	/s/	10529.27	437.13	310.23	60.14	0.39	0.14	65.71	10.90
	/θ/	14099.17	424.69	278.44	72.45	-0.58	0.18	90.32	19.49

015								
/s/	10293.32	814.73	214.73	52.53	0.23	0.28	61.84	13.10
/θ/	11132.86	1035.05	145.45	55.04	-0.08	0.23	48.03	9.92
017								
/s/	10481.59	1021.30	209.02	22.98	0.33	0.34	51.31	12.64
/θ/	10938.93	1252.30	104.59	53.59	-0.20	0.35	41.05	13.06
019								
/s/	9981.78	458.64	177.84	29.07	0.22	0.22	49.44	10.56
/θ/	10951.35	1066.32	111.64	119.25	-0.11	0.18	40.76	15.98
021								
/s/	10750.60	732.14	165.80	20.87	0.26	0.17	48.21	6.11
/θ/	10290.26	1593.91	100.54	67.84	0.22	0.33	41.09	12.64
022								
/s/	11082.26	1004.50	166.62	55.01	0.10	0.22	52.00	15.91
/θ/	10986.70	1990.23	95.20	52.46	-0.11	0.40	43.92	16.54
023								
/s/	9747.35	626.62	286.58	138.84	0.28	0.21	39.77	5.14
/θ/	11484.93	773.36	173.96	36.26	-0.17	0.20	48.32	7.81
024								
/s/	11266.36	551.98	176.18	24.99	0.18	0.26	93.85	17.98
/θ/	12036.09	917.57	185.07	90.32	-0.20	0.23	57.79	10.23
025								
/s/	11752.52	1255.70	313.40	227.01	-0.13	0.48	71.23	18.47
/θ/	11816.42	791.65	259.67	169.93	-0.31	0.48	70.49	26.51
028								
/s/	10798.00	521.48	147.28	21.48	0.12	0.24	72.70	9.06
/θ/	12842.54	1092.46	140.12	20.91	-0.67	0.31	57.30	12.49
029								
/s/	10847.21	998.29	179.72	18.65	0.06	0.47	56.78	10.40
/θ/	12288.01	456.82	192.17	67.20	-0.38	0.36	64.98	17.10
030								
/s/	10830.54	624.24	179.38	21.77	0.27	0.23	57.86	9.62
/θ/	10848.86	398.15	189.25	35.50	0.26	0.20	56.44	8.12
032								
/s/	9785.02	531.99	204.67	71.49	0.42	0.15	46.27	7.44
/θ/	11543.28	770.19	163.55	36.45	-0.31	0.25	42.87	7.79
033								
/s/	12721.53	1094.73	181.44	45.68	-0.38	0.21	73.34	25.98
/θ/	13000.55	1089.84	179.04	27.69	-0.37	0.44	84.00	27.69
034								
/s/	12388.68	512.16	163.75	51.11	-0.26	0.13	54.93	9.67
/θ/	13490.21	341.84	143.18	32.21	-0.54	0.20	90.47	14.09

035									
	/s/	11388.46	1441.35	208.05	26.62	0.22	0.24	58.10	9.60
	/θ/	12486.12	783.93	87.07	40.37	-0.34	0.14	63.08	11.20
036									
	/s/	10831.33	452.60	151.06	75.75	0.02	0.19	45.73	7.15
	/θ/	11257.07	865.81	147.55	23.48	-0.06	0.23	43.13	7.76
038									
	/s/	11580.61	1452.57	223.75	74.45	0.06	0.36	73.49	21.24
	/θ/	12189.51	782.03	202.16	34.83	-0.29	0.27	65.04	11.92
039									
	/s/	12583.17	1039.17	163.13	47.15	-0.40	0.23	68.74	17.69
	/θ/	11839.01	1259.94	121.44	22.37	-0.24	0.28	60.39	20.37
041									
	/s/	11153.97	644.89	182.17	34.68	0.40	0.25	75.53	7.98
	/θ/	11840.45	637.42	223.98	35.49	-0.15	0.35	81.79	10.55
042									
	/s/	10996.19	1092.35	171.36	49.46	0.31	0.32	56.08	10.45
	/θ/	14080.32	1113.26	172.06	36.81	-0.84	0.23	76.28	20.62
045									
	/s/	12973.61	1025.31	205.75	46.52	-0.35	0.40	88.58	17.26
	/θ/	13768.68	828.09	154.76	55.75	-0.87	0.38	88.47	32.15
046									
	/s/	10372.64	500.90	214.68	46.26	0.43	0.30	77.25	21.22
	/θ/	12186.09	1086.54	159.62	44.82	-0.28	0.23	66.81	17.60
047									
	/s/	13655.63	881.38	169.81	35.69	-0.73	0.39	71.55	18.71
	/θ/	13277.41	1016.18	215.03	64.48	-0.60	0.37	74.08	24.43
048									
	/s/	9831.71	930.98	139.63	20.76	0.11	0.28	31.24	6.05
	/θ/	9850.83	1466.60	42.47	40.99	0.00	0.51	33.84	12.73
049									
	/s/	11948.26	837.71	259.37	59.51	-0.24	0.23	81.91	14.68
	/θ/	11600.93	715.74	68.17	20.61	-0.24	0.23	55.78	9.56
050									
	/s/	12165.35	636.64	173.63	33.32	-0.54	0.18	61.25	9.81
	/θ/	12559.79	845.87	223.79	165.59	-0.47	0.19	55.47	14.59
051									
	/s/	12355.36	689.83	524.73	244.57	-0.01	0.24	80.88	17.52
	/θ/	14368.59	922.01	471.84	376.83	-0.82	0.35	86.53	26.81
052									
	/s/	11524.46	1071.41	211.45	46.80	-0.08	0.21	66.26	20.32
	/θ/	10379.12	820.86	24.81	5.14	-0.14	0.15	28.07	5.85

055								
/s/	11369.89	613.93	213.06	24.68	-0.18	0.22	59.31	12.11
/θ/	11529.83	1162.42	111.94	34.31	-0.28	0.26	47.66	12.07
058								
/s/	10082.81	670.22	288.43	195.86	0.20	0.13	56.16	8.37
/θ/	13014.85	567.13	269.62	145.20	-0.41	0.18	67.99	9.55
062								
/s/	12811.80	927.07	365.33	162.25	-0.28	0.36	78.05	16.14
/θ/	12399.54	816.40	250.49	81.14	-0.28	0.24	74.56	18.55
063								
/s/	10950.05	475.43	278.25	33.33	0.32	0.33	84.89	14.95
/θ/	12498.65	1711.45	121.22	66.18	-0.43	0.39	56.14	17.97
064								
/s/	11298.00	754.77	201.36	21.33	0.02	0.17	67.07	13.05
/θ/	11909.76	817.69	96.17	80.92	-0.36	0.20	56.06	12.66
065								
/s/	12480.20	1065.51	168.12	33.47	-0.35	0.27	71.81	15.02
/θ/	12734.65	819.04	116.75	97.40	-0.66	0.43	57.32	17.03
066								
/s/	10209.93	759.64	166.81	38.39	0.05	0.23	48.12	12.79
/θ/	10440.32	1092.11	111.14	30.02	-0.07	0.33	33.25	5.63
067								
/s/	10126.47	660.38	163.05	45.01	0.21	0.24	39.20	7.54
/θ/	11615.75	590.83	118.95	6.19	-0.16	0.25	49.96	8.19
068								
/s/	12184.20	815.76	195.24	63.64	-0.21	0.39	66.52	14.30
/θ/	11182.01	817.70	192.53	63.44	-0.07	0.32	47.75	10.55

Appendix B

Characteristics of SAILS Stimuli

Table B1

Acoustic Cues Differentiating Correct and Incorrect /s/ Productions in SAILS

Sue Stimuli	Correct /s/	Incorrect /s/		
	M (SD)	*M (SD)*	*t*	*p*
Level 1				
Centroid	6788.465 (497.977)	5551.661 (822.548)	1.89	.02
Duration	263.272 (44.642)	129.662 (85.600)	1.94	.02
Skewness	-0.674 (0.346)	-0.085 (0.331)	1.86	.03
Kurtosis	92.754 (19.910)	40.343 (12.438)	1.89	.002
Level 2				
Centroid	6839.438 (571.649)	5985.869 (526.450)	1.86	.04
Duration	254.952 (44.245)	283.352 (51.749)	1.86	.38
Skewness	-0.703 (0.493)	-0.403 (0.400)	1.86	.32
Kurtosis	87.728 (16.743)	46.186 (9.351)	1.94	.003
Level 3				
Centroid	6679.646 (642.525)	6130.754 (447.978)	1.89	.16
Duration	218.422 (20.919)	264.516 (72.678)	2.02	.23
Skewness	-0.645 (0.441)	-0.184 (0.385)	1.86	.12
Kurtosis	98.343 (45.454)	63.664 (23.378)	1.94	.19

Note. Independent *t*-tests were used to help determine which cues were used to distinguish correct and incorrect productions of /s/ across the different levels in SAILS.

Table B2

Bivariate Pearson Product-Moment Correlations Between Performance on SAILS Levels 1, 2, 3 and $d_{(a)}$ Values

	Sue 1	Sue 2	Sue 3	$d_{(a)}$centroid	$d_{(a)}$duration	$d_{(a)}$skewness	$d_{(a)}$kurtosis
Sue 1	1.00	.441**	.381**	.082	.133	.114	.149
Sue 2		1.00	.631**	.106	.071	.141	-.031
Sue 3			1.00	.096	.258	.251	-.102
$d_{(a)}$centroid				1.00	-.396**	.845**	-.548**
$d_{(a)}$duration					1.00	-.193	.404**
$d_{(a)}$skewness						1.00	-.368**
$d_{(a)}$kurtosis							1.00

Note. Sue 1 = Average performance on level 1 across the two assessment times; Sue 2 = Average performance on level 2 across the two assessment times; Sue 3 = Average performance on level 3 across the two assessment times.

Table B3

Between Group Differences in Performance on Each Level of SAILS as a Function of the Child's use of the Centroid, Duration, Skewness, and Kurtosis Cues to Differentiate /s/ and /θ/ in Production

		Sue 1	Sue 2	Sue 3
Centroid				
	Yes	81.67	65.21	68.13
	No	79.71	61.77	65.29
	df	39	39	39
	t	.82	1.33	.81
	p	.42	.19	.42
Duration				
	Yes	81.36	65.68	71.36
	No	80.26	61.58	61.84
	df	39	39	39
	t	.46	1.62	3.03
	p	.65	.11	.00
Skewness				
	Yes	81.25	64.82	68.21
	No	80.00	61.54	64.23
	df	39	39	39
	t	.49	1.19	1.08
	p	.63	.24	.29

Kurtosis				
	Yes	82.69	66.54	67.31
	No	80.00	62.50	66.79
	df	39	39	39
	t	1.07	1.48	.140
	p	.29	.15	.89

Note. Independent *t*-tests were used to divide the total group into children who used a certain cue to distinguish their /s/ and /θ/ productions (i.e., centroid, duration, skewness, kurtosis) and children who did not use that cue; Yes = Group of children who used the cue to distinguish their productions of target /s/ and /θ/; No = Group of children who did not use the cue to distinguish their productions of target /s/ and /θ/. Independent *t*-tests were then used to compare performance of the groups on each level of SAILS.