Acquisition of initial /s/-stop and stop-/s/ sequences in Greek

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ABSTRACT
Previous work on children's acquisition of complex sequences points to a tendency for affricates to be acquired before clusters, but there is no clear evidence of a difference in order of acquisition between clusters with /s/ that violate the Sonority Sequencing Principle (SSP), such as /s/ followed by stop in onset position, and other clusters that obey the SSP. One problem with studies that have compared the acquisition of SSP-obeying and SSP-violating clusters is that the component sounds in the two types of sequences were different. This paper examines the acquisition of initial /s/-stop and stop-/s/ sequences by sixty Greek children aged 2 through 5 years. Results showed greater accuracy for the /s/-stop relative to the stop-/s/ sequences, but no difference in accuracy between /ts/, which is usually analyzed as an affricate in Greek, and the other stop-/s/ sequences. Moreover, errors for the /s/-stop sequences and /ts/ primarily involved stop substitutions, whereas errors for /ps/ and /ks/ were more variable and often involved fricative substitutions, a pattern which may have a perceptual explanation. Finally, /ts/ showed a distinct temporal pattern relative to the stop-/s/ clusters /ps/ and /ks/, similarly to what has been reported for productions of Greek adults.

Keywords: Greek, consonant clusters, affricate, acquisition

INTRODUCTION

Children acquire the sound system of the ambient language in a remarkably short period of time. Within only a few years after birth, they can produce most of the consonants and vowels of their language with native-like competency. Moreover, they can produce them correctly within all of the relevant prosodic structures, including complex syllable shapes and longer words.

During the course of phonological development, some sounds and sound sequences are mastered earlier than others. Acquisition research, whether in normal or disordered development, has shown that several parameters, including type of segment, syllable structure, sonority, frequency, and perceptual salience all affect the order of acquisition of consonants and consonant clusters. While the first three factors have been widely studied in the literature, there is considerably less work on the role of frequency and perceptual salience on cluster acquisition. There is also relatively limited research on acquisition in languages other than English or cross-linguistic studies that can provide insights on 'universal' versus language-specific factors in acquisition. In the following review, we first discuss the role of each of these parameters in the order of acquisition of sounds and sound sequences focusing primarily on initial consonant clusters and affricates, and second, we outline the goals, research questions, and hypotheses of the current study.

The Role of Type of Segment in Acquisition

Beginning with Jakobson (1941/1968), it has been noted that some phoneme categories are acquired before others. In general, stops and nasals in consonant-vowel (CV) syllables are acquired early, while some fricatives (e.g., /θ/), /r/, and affricates are acquired later. Consonant clusters are also generally acquired later, after all members of the cluster are produced correctly as singletons (Smit, Hand, Freilinger, Bernthal, & Bird, 1990). Such differences in order of acquisition are commonly ascribed to universal constraints on production or perception. Categories that are relatively easy to produce or perceive will be acquired earlier, while those that are more difficult to produce or perceive will be acquired later (Kent, 1992; Locke, 1983).

Syllable Structure Complexity

Children progress from less complex to more complex syllable structures. They generally produce CV sequences with simple consonant articulations (e.g., /t/ or /ʃ/) before they produce more complex articulations, such as affricates and consonant clusters. The acquisition of both consonant clusters and affricates is protracted in many languages, and syllables with these segments are often produced incorrectly by both young typically-developing children (Kappa, 2002; Smit, 1993), and children with speech sound disorders (Barlow & Dinnsen, 1998; Ingram, Christensen, Veach, & Webster, 1980; Miccio & Ingrisano, 2000). Most research in this area has focused on the acquisition of consonant clusters. There are only a few studies that have specifically addressed the acquisition of affricates, despite the many similarities between the two.

For example, error patterns reported in the literature are quite similar for consonant clusters and affricates, the most common being reduction to a singleton (Ingram, 1989; Kappa, 1998; Smit, 1993). *Reduction* refers to the deletion of at least one of the consonants in a multi-consonant cluster or to the omission of the stop or fricative component of an affricate. In other cases, however, children produce a single consonant that is not a member of the target affricate or cluster (Olmsted, 1971).

While there is relatively little research on affricate acquisition, the existing data from typically-developing English-acquiring children suggests that the palato-alveolar affricate /tʃ/ generally appears after /t/, and at around the same time as /ʃ/ (e.g., Ingram, 1978), while stops (mainly alveolars) are the most common substitutions for affricates, especially in word-initial position (e.g., Ingram, 1989; Locke, 1983; Smit, 1993). Lléo and Prinz (1996, 1997) studied nine German and five Spanish-speaking children longitudinally and outlined a developmental progression from singletons with simple articulations (e.g., /t/, /ʃ/, /d/, /ʒ/) to affricates to consonant clusters. They further hypothesized that the three may be lawfully related such that clusters generally imply affricates, which in turn imply simple singletons, but not vice-versa.

Support for the existence of such a lawful relationship comes from a limited number of treatment studies of monolingual English-speaking children with phonological delays. Gierut and Champion (2001) found that treatment of three-element clusters with /s/ generalized to simple singletons and affricates, suggesting that affricates pattern like simple singletons in acquisition and are expected to be acquired before clusters. Gierut and O'Connor (2002) also observed that the acquisition of affricates occurred, for the most part, before the acquisition of consonant clusters.

However, affricates are not always acquired before clusters. In American English, two-member stop-glide clusters, specifically /tw/ and /kw/, are typically acquired before affricates (Smit, et al., 1990), and Grunwell (1987) suggests that even some /s/ clusters may emerge before affricates in a normal developmental sequence.

More cross-linguistic data are needed to evaluate the validity of the proposed relationship among simple singletons, affricates, and consonant clusters. Indeed, using the criterion of 75% correct production in any word position, data from Papadopoulou (2000; cited in Mennen & Okalidou, 2007) suggest that at least one cluster, /ks/, is acquired before the affricates /ts/ and /dz/ in Greek.

Frequency and Other Language-Specific Factors

Language-specific factors relating to syllable structure complexity and lexical phoneme frequency have also been reported to affect the rate at which consonant clusters and affricates attain mastery in different languages (e.g., Edwards & Beckman, 2008; Beckman & Edwards, in press). Consider, for instance, the case of Greek and Cantonese. The former has a very rich system of consonant clusters, with as many as 65 clusters in initial position, while Cantonese only has two clusters. Not surprisingly, cluster acquisition is much more protracted in Greek than in Cantonese (Mennen & Okalidou, 2007; So & Dodd, 1995). Moreover, both languages have a dental voiceless affricate, /ts/, which is considerably less frequent in Greek than in Cantonese. Cantonese-speaking 2- and 3-year-olds produce /ts/ at a much higher accuracy than Greek-speaking 2- and 3-year-olds. This difference in order of acquisition has been attributed to the difference in phoneme frequency of /ts/ in the two languages (Edwards & Beckman, 2008).

Lexical phoneme frequency has also been found to affect order of acquisition and error patterns within the same language. For example, /k/ is more frequent than /t/ in Greek and Greek 2-year-olds show greater accuracy for /k/ than /t/, while /t/ is more frequent than /k/ in English and English 2-year-olds show greater accuracy for /t/ than for /k/ (Nicolaidis, Edwards, Beckman, & Tserdanelis, 2003). To our knowledge, there is little research on the influence of phoneme frequency on cluster acquisition, except for Kirk and Demuth (2005), who found that frequency did not seem to be a major explanatory factor in order of cluster acquisition.

The Role of Sonority in Cluster Acquisition

Many investigators have reported that within clusters there appears to be a well-defined order of acquisition, at least for word-initial clusters in English (McLeod, vanDoorn, & Reed, 2001; Smit, et al., 1990). For example, stop-glide clusters are generally produced and mastered earlier than fricative-liquid clusters, and many two-member clusters emerge before three-member clusters (McLeod, et al., 2001). However, cluster reduction patterns are less predictable. Children do not consistently omit a consonant based on its position in the cluster or its place or manner of articulation. For example, English-speaking children frequently delete the fricative and retain the stop in fricative-stop clusters (e.g., [t] for /st/), but delete the stop and retain the glide in stop-glide clusters (e.g., [w] for /tw/). That is, cluster reduction patterns seem to depend, at least in part, on the consonant sequence. Furthermore, patterns of cluster reduction are similar across a number of children acquiring different languages (e.g., Locke, 1983; Yavaş, Ben-David, Gerrits, Kristoffersen, & Simonsen, 2008).

The *Sonority Sequencing Principle* (SSP) is the most commonly invoked explanation for both the order of cluster acquisition and error patterns (e.g., Clements, 1990; see also Pater & Barlow, 2003, for a sonority-based explanation of exceptions to SSP-based cluster reduction constraints). *Sonority* refers to the relative perceptual prominence of one sound class versus another, such that obstruents ("O", including stops, affricates, and fricatives), nasals ("N"), liquids ("L"), glides ("G"), and vowels ("V") comprise a scale of increasing sonority strength. The SSP states that the simplest, least-marked syllable is one in which sonority begins maximally low and rises towards the vocalic peak. The ideal syllable ends in a vowel; however, if postvocalic consonants are present, sonority should decline gradually (or remain level) from the nucleus of the syllable to the end of the coda.

The ideal conformation for syllables with onset clusters is Obstruent-Liquid-Vowel (OLV, as in /tri/), where the sonority rise from left periphery to peak is gradual and evenly distributed. Syllables with /s/-stop onset clusters (as in OOV /stu/) contain fricative-stop sonority reversals, however, and violate the SSP for the onset-to-peak (initial demisyllable) portions of syllables. Sonority theory predicts that syllable structures with least-marked sonority sequences will be acquired earlier in development than those with more-marked sequences or those with SSP violations, such as initial /s/-stop clusters (Clements, 1990).

If initial /s/-stop clusters are truly anomalous because they do not obey the SSP, then we might predict that they would appear less frequently in the world's languages than similar clusters that obey the SSP. This is not the case, however. Such clusters are found not only in English, but in many other languages (e.g., Dutch, Georgian, Greek, Italian, Hindi, Polish, Norwegian, Serbo-Croatian, Telugu, etc.). In contrast, initial stop-/s/ clusters, which obey the SSP, are considerably more rare, occurring in very few Indo-European languages, such as Greek, and in a few Amerindian (e.g., Wichita) and Austronesian languages (e.g., Tsou). While stop-/s/ clusters are rare, stop-liquid clusters also follow the SSP and are more common across languages (e.g., Greenberg, 1978). However, they are not more common than /s/-stop clusters (e.g., Jongstra, 2003). In a large typological study, Morelli (1999, 2000) also found that initial /s/-stop clusters were the most frequent obstruent cluster type.

A number of researchers have tested the SSP hypothesis by the order of acquisition of SSP-obeying and SSP-violating clusters. Yavaş et al., (2008) did not find a statistically significant difference in typically-developing children's productions of SSP-adhering and SSP-violating word-initial /s/-clusters across four languages (Dutch, English, Hebrew, and Norwegian). Cross-linguistic studies from disordered phonologies found that children acquiring English (monolingual and Spanish-English bilingual) were more accurate at producing consonant clusters which obeyed the SSP. However, Dutch-acquiring children did not show a difference between SSP-adhering and SSP-violating targets, while children acquiring Hebrew and Croatian showed greater accuracy for SSP-violating (e.g., /s/-stop) than SSP-following clusters. This was attributed to the larger number of clusters in these two languages that either violates the SSP or stays with level sonority sequencing between C_1 and C_2, a fact which may have affected children's sensitivity to the SSP-following/SSP-violating sub-groupings (Yavaş, 2010).

In English, the results are inconsistent. Some studies have found that /s/- stop clusters are acquired earlier than other clusters (e.g., Stoel-Gammon & Dunn, 1985), while others have found that they are acquired later (e.g., Smith, 1973; Smit, 1993). In Smith's (1973) diary study of normal phonological development, Amahl acquired the /s/-clusters later than most other clusters. From case studies of disordered development, some children acquired all the /s/-clusters before other clusters (e.g., Barlow, 1997; Gierut, 1999). However, Chin (1996) reported on one child who acquired non-/s/ clusters first, while another child acquired the two types of clusters at the same time.

With reference to reduction patterns, the *Sonority Hypothesis* (SH) (e.g., Wyllie-Smith, McLeod, & Ball, 2006) predicts that when children reduce onset clusters they will retain the least sonorous member of the cluster so that initial demisyllables will show a maximum rise in sonority from the left syllable periphery to the vocalic peak. Although this pattern is seen when the second consonant of a cluster has not yet been acquired (e.g., production of [ti] for /tri/), the consonant cluster acquisition literature is replete with examples that violate the SH. For instance, Fikkert (1994) found that Dutch-acquiring children often reduced initial fricative-nasal (/sn/-/sm/), stop-nasal, stop-liquid, and fricative-liquid clusters to the more sonorous second member of the cluster. Lléo and Prinz (1996) also noted that Spanish-speaking children as a group preserved the more sonorous segment for a large number of target initial clusters.

The Role of Perceptual Salience in Acquisition

Because of these many exceptions to the SSP, some researchers have suggested that the SSP should be revised to also consider the role of perceptual constraints. For example, Wright (2004) proposed a reformulation of the SSP that was based on perceptual cue robustness. He defined *cue* as: "information in the acoustic signal that allows the listener to apprehend the existence of a phonological contrast" (p. 36), and *cue robustness* as involving: "…cue redundancy [the result of articulatory (gestural) overlap], resistance of cues to environmental masking, the ability of cues to survive momentary distractions on the part of the listener, and the exploitation of the auditory system's tendency to boost certain aspects of the signal" (p. 42). Consequently, since speech frequently occurs in situations that include environmental masking of some kind, presence of more robust acoustic cues increases the likelihood that the contrast encoded by those cues will survive degradation or interference in the auditory signal.

This has implications for the preferred consonant sequences across languages, as well as in the developing system. For instance, as Wright points out, the commonly observed pattern of an alternating consonant and vowel (CVCV) is also the most robust in terms of presence of redundant cues in the acoustic signal, since each transition from vowel to consonant provides information about the vowel's quality, as well as the place, manner, and voicing of the adjacent consonant. Moreover, prevocalic /s/-stop sequences are favored cross-linguistically over stop-stop and stop-/s/ sequences, a preference which Wright attributes to acoustic factors: Sibilant fricatives have internal cues that help with their identification independently of context, while stop bursts, which are crucial for the identification of stop place of articulation, are acoustically salient only before vowels (p. 50).

Based on this analysis, we would predict that word-initial stop-/s/ sequences would be more protracted in acquisition relative to /s/-stop sequences, since they are less perceptually salient. In other words, /s/-stop clusters in initial position have a more robust encoding of place of articulation cues for the stop consonant compared to their reverse image (i.e., stop-/s/ clusters in initial position), since stop place of articulation is signaled both in the spectrum of the fricative noise and in the stop burst, as well as in the formant transitions of the following vowel (e.g., Engstrand & Ericsdotter, 1999). In addition, the audibility of the stop burst is less vulnerable in the context of a following vowel rather than a sibilant, which is more likely to mask the burst release. However, it is difficult to evaluate the above claim by looking at languages such as English, because English does not allow stop-/s/ clusters in initial position.

Cluster Acquisition in Greek

There is relatively limited research on cluster acquisition in Greek. A recent large scale study by Sanoudaki (2007) examined the acquisition of /s/-obstruent clusters /sp/, /st/, /sk/, /sf/, /sx/, obstruent-sonorant clusters /tɾ/, /kl/, /fl/, /xɾ/, /vɾ/, and obstruent-obstruent clusters /ft/, /xt/, /ɣð/, /vɣ/ in fifty-nine typically-developing children between the ages of two and five years, recorded in Southern Greece (Crete). Sanoudaki used a nonword repetition task to elicit the target sounds in word-initial and medial (intervocalic) position, the only positions where consonant clusters occur in Greek, except for loanwords. Similar accuracy rates were obtained for /s/-obstruent and obstruent-sonorant clusters, whereas children were less accurate in their productions of obstruent-obstruent clusters. However, this experiment did not provide quantitative information on error patterns, and it did not examine the clusters /ps/, /ks/, or the affricate /ts/.

Studies on the acquisition of /s/-stop and stop-/s/ sequences in Greek have focused on their order of mastery and the observed substitution patterns at different stages in development. No study has directly compared /s/-stop to stop-/s/ clusters and affricates, and while there are some data on the error patterns observed during the acquisition of these sequences, these are generally single case studies (e.g., Kappa, 1998; Kappa, 2002; Tzakosta, 2001). The evidence, however, suggests that both /s/-stop and stop-/s/ sequences are typically reduced to the stop consonant, although reduction to the fricative for stop-/s/ targets has also been reported (e.g., Papadopoulou, 2000; cited in Mennen & Okalidou, 2007).

The reported age of acquisition for the affricate in Greek is one of the most variable across studies. For example, according to the Panhellenic Association of Logopaedics (1995), /ts/ was produced correctly at 4;6-5;0 (years; months), but at 3;7-4;0 in Papadopoulou's (2000) study using the 75% criterion, and at 4;1-4;6 using the 90% criterion. The affricate was, in general, acquired either before or at approximately the same time as the clusters /ps/ and /ks/, although direct cross-study comparisons are made difficult by differences in research methodologies and sample sizes. All available studies, however, suggest that the most active period of acquisition of two-element /s/-clusters and the affricate /ts/ is between 3;6 and 4;6 years of age (e.g., Mennen & Okalidou, 2007).

Table 1 shows the number of words beginning with singleton /p, t, k, s/, and /sp, st, sk/, /ps, ts, ks/ consonantal sequences in the 20,000 most frequent words (lemmas) from the ILSP database (Hatzigeorgiu, et al., 2000). The database was based on a morphologically analyzed corpus of adult newspaper text (Hatzigeorgiu, et al., 2000; see also Nicolaidis, et al., 2003). The role of frequency in the acquisition of stop-/s/ and /s/-stop sequences will be examined in the discussion section.

Insert Table 1 about here

The Current Study

To date, virtually all of the studies that have examined the order of acquisition of SSP-adhering and SSP-violating clusters were based on datasets which contained clusters with different sounds. That is, clusters which did not violate the SSP generally contained later-developing sounds, such as /l/ and /r/, as compared to the /s/-stop clusters. Clusters are not generally produced correctly until children can correctly produce both of the singletons that comprise the cluster. Therefore, it is difficult to compare the acquisition of /s/-stop clusters to that of SSP-obeying clusters in languages such as English, because the SSP-obeying clusters generally contain later-developing sounds than the SSP-violating clusters.

In order to separate SSP constraints from sound acquisition artifacts during /s/ cluster acquisition, it would be best to control the composition, location, and prosodic influences on clusters that would otherwise differ only by their SSP profiles (e.g., onset /s/-stop versus stop-/s/ sequences). English phonotactics do not afford this type of comparison, but Greek is one of the few languages that contains both /s/-stop (/sp/, /st/, /sk/) and stop-/s/ onset clusters (/ps/, /ks/), as well as the affricate /ts/. Because we can control for the identity of the individual sounds in clusters and because both /s/-stop and stop-/s/ clusters are frequent in words that are usually familiar to children (e.g., house /ˈspiti/, fish /ˈpsaɾi/, cousin /ˈksaðeɾfos/) the purpose of the current study was to examine the acquisition of /s/-stop and stop-/s/ clusters in Greek.

The study reports findings from a cross-sectional investigation into the acquisition of these sequences. Given the limited data available on Greek typical acquisition, we also included accuracy data on the singleton consonants comprising these sequences (i.e., /p/, /t/, /k/, /s/). We did this to also ensure that children were producing the single members of each cluster type correctly before examining their productions of consonant clusters.

In addition, we were interested in the acquisition and timing pattern of the affricate /ts/ relative to that of the clusters /ps/ and /ks/, as the phonological status of /ts/ as an affricate or cluster in Greek is somewhat controversial (Arvaniti, 2007; see also Pagoni, 1995 for a theoretical analysis of the status of /ts/ within Government Phonology).

The majority of the phonological arguments as to the phonemic status of /ts/ are theoretical, based on distributional or morphological grounds. The limited phonetic evidence available so far suggests that /ts/ is *phonetically* produced as an affricate as opposed to the other stop-/s/ sequences /ps/ and /ks/, which are produced as consonant clusters (Arvaniti, 1987; Fourakis, Botinis, & Nirgianaki, 2003; Tserdanelis, 2005; see Arvaniti, 2007, for a review). Specifically, when the sibilant is part of /ts/ it has a significantly shorter duration than when it occurs in the /ps/ and /ks/ clusters. This could be indicative of /ts/ being produced as an affricate, since articulatory data from English suggests that the release of the affricate /ʧ/ starts earlier than for the stop /t/ as the groove is anticipated (Mair, Scully, & Shadle, 1996). This may explain the shorter duration of /ts/ compared to, for example, /ps/ and /ks/. The latter two involve separate articulators and therefore the coordination and timing of the gestures may be expected to be different. That is, anticipation of the tongue blade gesture for /s/ may be expected during the stop closure, but the release of the stop may occur later as it involves a separate articulator, i.e. the tongue dorsum for /k/ and the lips for /p/.

However, this argument needs to be tested with data from Greek before a stronger claim can be made. It is not the goal of this paper to make inferences on the phonemic status of /ts/. As Arvaniti (2007) points out "strong, phonetic evidence that [ts] is an affricate does not necessarily mean that it should be treated phonologically as a phoneme ... The phonemic status of [ts] should primarily rest on phonological arguments; those available so far do not provide absolute support for one or the other analysis" (p. 117).

The present study was designed to examine the role of major parameters such as sonority, perceptual salience, and frequency in the acquisition patterns of SSP-obeying stop-/s/ sequences and SSP-violating /s/-stop clusters in Greek. We were also interested in examining whether the phonetic difference between /ts/ as compared to /ps/ and /ks/ that has been observed in timing patterns (e.g., sibilant duration) of Greek adults' productions would be present in the children's data, as well. Such a finding would suggest that young Greek-acquiring children are sensitive to this fine-grained phonetic detail of their native language, and would provide evidence that /ts/ is phonetically an affricate in child speech, as well as in adult speech.

The following research questions and their associated hypotheses were addressed:

1. Which sequences are acquired first in Greek—SSP-obeying or SSP-violating? Can sonority account for the observed patterns? Alternatively, are perceptually less salient sequences more protracted in acquisition? We hypothesize that stop-/s/ sequences may be more protracted in acquisition relative to /s/-stop sequences, since they are less perceptually salient.

Perceptual salience is expected to interact with other factors, however, such as syllable structure complexity and frequency during affricate and cluster acquisition. Therefore, we expect that children will generally progress from less complex (i.e. singletons) to more complex syllable structures, and that less frequent sequences can be more protracted in acquisition.

2. Do error patterns vary during the acquisition of cluster types that differ in terms of the SSP and/or perceptual salience? Are more variable error patterns found for less perceptually salient sequences? We predict that errors for /s/-stop sequences will be relatively stable due to their greater perceptual salience and that they are likely to involve reduction to a plosive, in line with the SH and previous studies on the acquisition of this cluster type. We also hypothesize that variability in error patterns will be greater in the case of stop-/s/ clusters, since they are assumed to be less perceptually salient. Errors are likely to involve reduction to a fricative, as well as to a plosive.
3. Is there evidence that the temporal difference observed for Greek adults between /ts/ and the stop-/s/ clusters /ps/ and /ks/ is present in the children's data, as well? If we find this difference, it will be indicative of /ts/ being phonetically produced as an affricate in Greek from early stages of acquisition.

Building on previous findings, this study should contribute to current knowledge on phonological acquisition in Greek by offering new data and analyses. It differs from previous studies in that it examines clusters containing the same sounds in different vowel contexts in the same prosodic position; it includes a large sample of children, as well as adults; and it provides experimental data on the temporal characteristics of the affricate /ts/ and other stop-/s/ clusters in Greek child speech.

METHODS

Participants

Study participants included children and adults. With regard to the children, fifteen typically-developing male and female participants were included at each of the following age ranges: 2;0 to 2;11, 3;0 to 3;11, 4;0 to 4;11, and 5;0 to 5;11. All children were monolingual native speakers of Greek and the data were collected in their native country (Thessaloniki, Greece) by a native Greek speaker from the same dialect region. Children were recruited from local daycare centers and through personal contacts. All children were participants in a larger cross-linguistic study (Edwards & Beckman, 2008) examining the effects of phoneme and phoneme sequence frequency on children's acquisition of word-initial obstruents in six languages (English, Greek, Japanese, Cantonese, Mandarin, and Korean).

Children were determined to be typically-developing based on parent and teacher reports. All had a non-verbal IQ score at or above 85 (Burgemeister, Blum, & Lorge, 1972), had age-appropriate oro-motor skills (Kaufman, 1995), and had passed a hearing screening using otoacoustic emissions at 2000, 3000, 4000 and 5000 Hz. Demographic data is provided in Table 2. Fifteen native Greek-speaking adults (8 males and 7 females) also participated in the study. They were all from the same dialect region (Thessaloniki) and their age ranged between 20 and 35 years. They all passed a hearing screening using otoacoustic emissions at 2000, 3000, 4000, and 5000 Hz, similarly to the child participants, and completed a short questionnaire about their speech and language background and development.

The adults had no self-reported or otherwise evident problem with speech and/or language. No formal screening measures for evaluating speech and language were used. The adult participants were recruited from the Aristotle University of Thessaloniki community and through personal contacts. They were told that they would participate in a study on Greek children's phonological development. All adults signed a consent form and were paid for their participation. Their data are included below only in the duration analysis.

Insert Table 2 about here

Stimuli

The stimuli were word-initial /p/, /t/, /k/, /s/, /sp/, /st/, /sk/, /ps/, /ts/, ks/ embedded in 2 or 3-syllable real words before all the Greek vowels /a/, /e/, /i/, /o/, /u/. All words were stressed on the first syllable. One stimulus word per vowel context was elicited for all sequences, with the exception of /sp/, /ps/, and /ks/. These clusters could not be elicited before the vowel /u/ because there are no (pictureable) Greek words beginning with /spu/, /psu/ or /ksu/ that also have first syllable stress. There were also two stimuli for /ts/ before each of the vowels /i/, /a/ and /u/ and two stimuli for /t/, /k/ and /s/ before each vowel, because these words were elicited as part of the larger cross-linguistic study of word-initial voiceless obstruents. The complete list of stimuli is given in the Appendix.

Each target word was paired with a culturally-appropriate color photograph that was expected to be familiar to the children. All pictures were edited to fit on a fixed-size window on a laptop computer screen. A female native speaker of Greek (the first author) recorded multiple repetitions of each stimulus item in a child-directed speech register. The tokens that were selected for presentation had been discriminated with at least 80% accuracy by five adult Greek native speakers.

Procedure

Data collection took place in a quiet room at the children's preschool or home. Children were tested one at a time in two to three testing sessions depending on the age and attention span of the child. The majority of the youngest two-year-olds were tested in the presence of a caregiver at home, since Greek children do not typically attend preschool before the age of 2;6. Data collection was completed within a one-week time period for each child.

The target productions were elicited during a picture-prompted word-repetition task. The selected picture and its associated sound file were presented concurrently to the participants from a laptop with a 14-inch computer screen using a program specifically written for the purposes of this study. The sound file was played over speakers mounted to the left and right of the computer screen. The picture was displayed prominently against a background which varied in color from one trial to the next. The display included a picture of a duck walking up a ladder on the left side of the screen to provide visual feedback to the children about how close they were to completing the task.

An AKG C 5900M/TM 40 supercardioid condenser microphone was placed on a microphone stand with its back to the computer and head positioned to be roughly 15 cm from the child's mouth. Alternatively, if a child was fidgety, the microphone was held in front of the child's mouth by the experimenter. Children were instructed to repeat each word as they heard it and their productions were digitally recorded on a Marantz PMD 660 flashcard recorder, at a 44,100 Hz sampling rate.

The participants were instructed to say each picture name after they heard the audio prompt. This audio prompt was replayed and/or the children were asked to repeat their responses only if: (a) the child said an incorrect word (e.g., the child said αυγό [a'vɣo] "egg" when prompted with τσόφλι ['tsofli] "egg shell"), (b) there was excessive background noise, (c) the child spoke too softly, or (d) did not respond at all. The first transcribable response for each item that followed a single exposure to the audio prompt was used for all subsequent analyses.

Transcription

The first author judged the accuracy of every elicited singleton or cluster with /s/, as she listened to each response and examined the acoustic waveform. The affricate /ts/ and the individual members of the consonant clusters /sp/, /st/, /sk/, /ps/, and /ks/ were coded as either correct or incorrect. If incorrect, a phonetic transcription of the error was provided.

We treated the affricate as a single consonant during transcription, but transcribed clusters as a sequence of consonants using manner as a cue to whether the error was on the first or the second member of the cluster. For example, if the child's error shared the same manner of articulation with one of the two cluster elements, as in ['θcilos] for /ˈskilos/ ([ˈscilos]) "dog", where the error was a fricative, we labeled the production as containing an error for the first member of the cluster, the sibilant /s/, but as having a correct stop consonant. Unclear cases where it was impossible to decide whether the error was on the first or the second member of the cluster (e.g., metathesis errors, such as ['ksala] for /'skala/ "staircase") were labeled as 'whole cluster substitutions'. In these cases, both members of the cluster were coded as incorrect and a phonetic transcription of the entire CCV sequence was provided.

To assess transcription reliability, a second native speaker (the second author) independently transcribed 10% of the data (productions of one 2-year-old, two 3-year-olds, two 4-year-olds and one 5-year-old). The phoneme-by-phoneme inter-transcriber agreement for accuracy was 92% for the singletons and 86% for the clusters. The phoneme-by-phoneme inter-transcriber agreement for error type was 88% for the singletons and 81% for the clusters.

Duration Measurement

Only correctly produced tokens were included in the duration analysis. Using the Praat (version 4.5.18) signal-processing software (Boersma & Weenink, 2001), the onset and offset of /s/ were identified by the first author, who used both the waveform and the spectrogram. Spectrographic settings for view range were placed at 0.0-11000.0 Hz (for children) and from 0.0-9000.0 Hz (for adults). The dynamic range was set at 40.0 dB.

The beginning of /s/ in words starting with singleton /s/ and /s/-stop sequences was defined as the onset of the aperiodic high-frequency noise characteristic of voiceless fricatives. The onset of /s/ in stop-/s/ sequences /ps/, /ks/ and /ts/ was marked at the upward swing of the closest zero crossing right after the first stop burst, evidenced in the spectrogram by the end of the short vertical line representing the noise of the release burst. In case of multiple bursts, the onset of /s/ was marked after the end of the last of a set of successive bursts that were separated with less than or equal to 5 ms of distance from each other. In the few cases where there was no clear burst, the onset of /s/ was marked at the onset of frication, using the same criteria described above for singleton /s/ and /s/-stop targets.

Criteria used to determine the offset of /s/ in /s/-stop clusters were attenuation of the amplitude of the signal and the end of aperiodic high-frequency noise. The offset of /s/ for singleton /s/ and stop-/s/ targets was defined as the first vocal pulse following a clearly periodic downswing of a wave cycle.

Reliability of the measurements was determined by having a graduate student with training in phonetics independently align 10% of the child data. The mean absolute difference in duration between the two intervals was 8.07 ms for singleton /s/ (range: 0-39.64 ms), 7.33 ms for /s/ in /s/-stop sequences (range: 0.018-33.45 ms) and 3.06 ms for /s/ in stop-/s/ sequences (range: 0-20.77 ms).

Data Analysis

Coding of errors. All instances of children's productions that were transcribed as incorrect were transcribed phonetically. The transcriptions were then used to group the errors into the six types described in Table 3.

Insert Table 3 about here

Statistical analysis. We performed two types of hierarchical logistic regression analysis (Raudenbush & Bryk, 2002) on the transcribed accuracy and error categories and a hierarchical linear regression analysis on the fricative duration measurements. All analyses were conducted using the statistical software HLM 6.0 (Raudenbush, Bryk, Cheong, & Congdon, 2004). In the first type of analysis, the dependent variable was accuracy of clusters and affricates as whole units, coded as either correct or incorrect. In the second type of analysis, the dependent variable was error category, coded as either stop substitution or other. In the third type of analysis, the dependent variable was fricative duration, measured in milliseconds. This variable was log-transformed before the hierarchical linear model was applied. For all analyses, the independent variable at the lower level (level-1) was sequence type, which could be any one of the six target sequences under study, with /ts/ being the reference category. The independent variable at the higher level (level-2) was age, which was quantitative in the first two models (age in months), but categorical in the third model (adult versus child). Furthermore, differences among the various sequence types in each model were further explored with contrast tests.

We chose the hierarchical modeling approach because of the nested structure of the data. Since each child responded to more than one stimulus, these responses (the micro-unit) can be considered to be nested within the individual child (the macro-unit). One of the strengths of hierarchical linear models is that they explicitly recognize that responses coming from the same child may be more similar to one another than they are to responses coming from a different child and may not, therefore, provide independent observations. In other words, these approaches explicitly model both the lower-level (the stimuli responses) and the higher-level (the individual) random-error components, therefore recognizing the partial interdependence of responses coming from the same child. This is in contrast to traditional regression analysis, where lower-level and higher-level random errors are not separately estimated. In addition, these models allow one to investigate both lower-level and higher-level variance in the dependent variable while maintaining the appropriate level of analysis for the independent variables.

RESULTS

Accuracy Analysis

Figure 1 shows the percent correct production of sequences with /s/ and singleton consonants (presented here for comparison purposes only) for each of the four age groups. Several observations can be made. First, the 2-year-olds produced very few clusters correctly and, not surprisingly, accuracy increased with age. By age four, children produced all target sequences with at least 80% accuracy. Second, singleton stop consonants were produced more accurately than the singleton /s/, and singleton /s/ was produced more accurately than either the clusters or the affricate /ts/. This pattern occurred more prominently in the 2-year-olds and the 3-year-olds. Third, the affricate /ts/ was produced less accurately than the other singletons, similarly to all of the consonant clusters in this study. Finally, /s/-stop sequences were produced more accurately than stop-/s/ sequences, especially in the case of the 3-year-olds.

Insert Figure 1 about here

Figure 2 shows mean percent correct productions for the six sequence types /sp/, /st/, /sk/, /ps/, /ts/, /ks/, as a function of the child's age in months. The regression curves show the probability of correct response of the six sequence types as estimated in the hierarchical logistic model described in Table 3. There is clearly an age effect, with the oldest children being very accurate on all sequence types, and the youngest children producing very few consonant sequences correctly. In the middle of the age range we can see a more clear separation as a function of sequence type, such that the /s/-stop sequences were produced more accurately than the stop-/s/ sequences.

Insert Figure 2 about here

We used a hierarchical logistic regression model (Raudenbush & Bryk, 2002) to analyze the effects of age, sequence type (/s/-stop or stop-/s/) and place of articulation (/p/, /t/, or /k/). The data set included 1755 responses (level-1) from 60 children (level-2). There were six predictors in the model, with five at the stimulus response level (level-1) and one at the child participant level (level-2). The level-1 predictors were the following: sequence /sp/, sequence /st/, sequence /sk/, sequence /ps/, sequence /ks/. These predictors were dummy coded, and /ts/ was used as the reference category. The level-2 predictor was the children's age in months. This level-2 predictor was centered around its grand mean.

The estimated parameters of the model are given in table 4. Contrast tests were also performed to evaluate the differences between /s/-stop and stop-/s/ sequences, as well as between homorganic and non-homorganic sequences.

Insert Table 4 about here

The results shown in table 4 revealed significant effects for the coefficients associated with each of the /s/-stop sequences, as well as the coefficient for age. Age was a significant predictor of accuracy, with older children more likely to produce correct responses than younger children. In addition, the /s/-stop sequences /sp/, /st/, /sk/ were more likely to be produced correctly relative to /ts/ (the reference category), while there was no significant difference in accuracy between /ts/ and the stop-/s/ sequences /ps/ and /ks/. However, the positive sign of the coefficients for /ps/ and /ks/ suggests that they tended to be more accurate than /ts/ for a hypothetical 43-month-old (corresponding to the grand average of the ages of the children included in the study), who has typical production.

The first contrast test was done to evaluate whether the /s/-stop sequences /sp/, /st/, /sk/ as a group differed significantly from the stop-/s/ sequences /ps/, /ts/, and /ks/. The result showed that the difference between the two groups was significant ($\chi^2 = 6.170$, $df = 1$, $p = 0.012$). The /s/-stop sequences were significantly different from the stop-/s/ sequences in terms of probability of correct response, with /s/-stop sequences being more accurate than stop-/s/ sequences overall. Moreover, a similar result was obtained in the comparison of /sp/, /st/, /sk/ versus /ps/ and /ks/ ($\chi^2 = 8.223$, $df = 1$, $p = 0.004$).

The next contrast test performed examined the effect of homorganicity and place of articulation on accuracy of production. We were interested in whether /st/ and /ts/ might be more accurate than the other sequences because /s/ and /t/ are produced at the same place of articulation. We also wondered whether either the labial or velar place of articulation for the stop consonant resulted in higher accuracy for both the stop-/s/ and the /s/-stop sequences. To this end, we compared /sp/ versus /st/ ($\chi^2 = 0.248$, $df = 1$, $p = >.500$), /sp/ versus /sk/ ($\chi^2 = 0.001$, $df = 1$, $p = >.500$), /st/ versus /sk/ ($\chi^2 = 0.246$, $df = 1$, $p = >.500$), and /ps/ versus /ks/ ($\chi^2 = 0.007$, $df = 1$, $p = >.500$). None of these pair-wise comparisons was statistically significant. This suggests that neither place of articulation nor homorganicity is a significant predictor of accuracy in the case of consonant clusters.

Error Analysis

In this analysis, we examined the substitution patterns that children produced when the target sequences were not produced correctly. We were interested in whether errors on /s/-stop sequences differed from errors on stop-/s/ sequences and also whether errors for the affricate /ts/ differed from errors on the two other stop-/s/ sequences, /ps/ and /ks/.

Figure 3 shows the substitution patterns for each sequence type for the 2-year-olds and the 3-year-olds. We present error data from the younger age groups only, because by age four, children were at least 80% accurate on all the sequences examined. It can be observed that in the stop-/s/ sequences, /ps/ and /ks/ patterned more like each other and differently from the affricate /ts/. On the other hand, the /s/-stop clusters were strikingly similar with respect to their error patterns, the most frequent substitution being a stop. This substitution pattern was similar to what has been observed in other languages, such as English (e.g., Smit, 1993).

In contrast, errors were considerably more variable for the stop-/s/ sequences /ps/ and /ks/, and in the case of /ps/, the most frequent substitution was not a stop, but either a fricative or another stop-fricative sequence. The most frequent substitution for /ts/ was a stop consonant. This is also consistent with what has been reported previously for affricates, particularly in word-initial position (e.g., Ingram, 1989; Locke, 1983; Stoel-Gammon & Dunn, 1985).

Insert Figure 3 about here

On the basis of this, we next decided to group errors as stop substitution or other, since stop substitutions were the most frequent for both /s/-stop sequences and /ts/. Moreover, such a classification would enable us to test whether /s/-stop versus stop-/s/ sequences would be equally likely to be substituted by a stop, as the literature predicted, and whether errors for /ts/ versus /ps/ and /ks/ would also be more likely to be stop errors as opposed to some other category. This would have implications for the pattern of reduction that children show during the acquisition of affricates and consonant clusters.

Figure 4 illustrates the percentage of stop substitutions, as a function of the child's age in months. The regression curves show the probability of a stop substitution for the six sequence types as estimated in the hierarchical logistic regression model described in Table 5. It can be observed that the /s/-stop sequences patterned together with /ts/, with more than 50% of all substitutions for the three being stop errors. In contrast, very few stop substitutions occurred for /ks/ and even fewer for /ps/. Thus, /ts/ did not behave like the other stop-/s/ sequences /ps/ and /ks/, but appeared to show more stop substitutions, similar to the /s/-stop sequences.

Insert Figure 4 about here

In order to test the statistical significance of these observations, we applied a second hierarchical logistic regression model similar to the one used for the accuracy analysis. The dependent variable in this case was the error made for a given consonant sequence coded as 1 if the manner of articulation of the error was a stop and 0 otherwise. The data set included 613 error responses (level-1) from 30 children (level-2). The predictors entered in the model were the same as the ones used in the accuracy analysis. Similarly to the first model, contrast tests were additionally performed to test the effect of sequence type and homorganicity on the type of error made. The estimated coefficients for the error analysis are given in table 5 below.

Insert Table 5 about here

The results shown in table 5 reveal significant effects for the coefficients associated with the two stop-/s/ clusters /ps/ and /ks/. Specifically, the substitution pattern for /ts/ was significantly more likely to be a stop consonant, relative to the substitution patterns for the other stop-/s/ sequences. The non-significant effects for the coefficients associated with /sp/ /st/, and /sk/ suggest that these sequences also had stop consonant substitutions. The negative sign of the coefficient for the target sequence types suggests that all sequences (with the exception of /sp/) were associated with fewer stop substitutions relative to /ts/ (the reference category). The sequence /sp/ showed an almost identical pattern to /ts/, having the highest percentage of stop errors. The negative coefficient for age indicates that stop substitutions decreased as age increased. This was expected, since older children were more likely to make errors that did not reduce the sequence, but instead were simple substitutions of place or manner for one or both parts.

Moreover, the results of the contrast tests also revealed that the /s/-stop sequences /sp/, /st/, /sk/ were significantly different from the stop-/s/ clusters /ps/ and /ks/ in the probability of having a stop substitution as opposed to some other substitution category ($\chi^2 = 44.545$, $df = 1$, $p = 0.000001$). The same result was obtained for /ts/ compared to the non-homorganic clusters /ps/ and /ks/ ($\chi^2 = 21.148$, $df = 1$, $p = 0.000049$). Among the /s/-stop sequences, /st/ was not significantly different from /sk/ in the probability of having a stop substitution ($\chi^2 = 0.094$, $df = 1$, $p > .500$), and nor was /sp/ significantly different from /sk/ ($\chi^2 = 3.075$, $df = 1$, $p = 0.076$). However, /sp/ was more likely to have stop substitutions compared to /st/ ($\chi^2 = 3.942$, $df = 1$, $p = 0.044$), and /ks/ was more likely to have stop substitutions compared to /ps/ ($\chi^2 = 4.646$, $df = 1$, $p = 0.029$).

Duration Analysis

The duration analysis focused primarily on differences between the affricate /ts/ and the two stop-/s/ clusters, /ps/ and /ks/. Figure 5 gives median fricative durations for the /s/-stop and stop-/s/ sequences and for the singleton /s/ when produced correctly by children and adults, pooled across tokens. Median instead of mean values are shown, because the former are less sensitive to outliers and are, thus, a more reliable measure of central tendency. Only the children who produced at least one token for each of the six consonant sequence types were included in the analysis. This excluded all of the 2-year-olds, 11 of the 3-year-olds, and 2 of the 4-year-olds.

As we can see in Figure 5, the place of articulation of the stop did not seem to have a consistent effect on fricative duration in the /s/-stop sequences, which showed a similar pattern across all places of articulation and all age groups. In contrast, the stop-/s/ sequences showed a distinctly different pattern. While similar fricative durations were observed for the stop-/s/ sequences /ps/ and /ks/ across age groups, this was clearly not the case for /ts/, which was characterized by much shorter /s/ duration. Finally, as expected, the singleton /s/ had the longest duration of the target types in all age groups, and children's segments were generally longer than those of the adults.

Insert Figure 5 about here

We used a hierarchical linear model with two levels to analyze these data. In this model, the data came from 1145 responses produced by 47 participants. The dependent variable was fricative duration measured in milliseconds. Sequence type was the explanatory variable at the stimulus response level (level-1), and age group was the explanatory variable at the child participant level (level-2). The singleton /s/ was not included in the model. Age was coded as a categorical variable this time (i.e., adult versus child), because only the older children were included in the analysis. We were interested in whether children as a group showed a different pattern from the adults. The results of the regression analysis are presented in Table 6.

Insert Table 6 about here

These results showed significant effects for the coefficients associated with all of the consonant clusters. The /s/-stop and stop-/s/ clusters had significantly longer fricative durations relative to /ts/ (the reference category). There was also a significant effect of age in the predicted direction. Specifically, children had significantly longer durations compared to the adults, as suggested by the negative coefficient for age.

We also examined these patterns with contrast tests. The first contrast compared the /s/-stop sequences (/sp/, /st/, /sk/) to all the stop-/s/ sequences (/ps/, /ts/, /ks/). It was found that there was a significant difference between the two groups in fricative duration ($\chi^2 = 4694.680$, $df = 1$, $p = <0.001$). A similar result was obtained when comparing the /s/-stop sequences to the stop-/s/ sequences, excluding /ts/ ($\chi^2 = 96.447$, $df = 1$, $p < 0.001$). The next set of contrast tests compared the /s/-stop sequences to one another. None of these pair-wise comparisons was significant. Similarly, /ps/ was not significantly different from /ks/ ($\chi^2 = 0.0008$, $df = 1$, $p > .500$).

Finally, a comparison between non-homorganic /s/-stop and stop-/s/ sequences (/sp/, /sk/ versus /ps/, /ks/) revealed a significant difference in fricative duration between the two groups ($\chi^2 = 0.013$, $df = 1$, $p = 0.005$). These results show that /ts/ was associated with a much shorter /s/ duration compared to both the non-homorganic stop-/s/ sequences (/ps/ and /ks/) and the homorganic or non-homorganic /s/-stop sequences.

DISCUSSION AND CONCLUSION

This study was designed to compare the acquisition of initial /s/-stop and stop-/s/ clusters, as well as the affricate /ts/ in Greek, a language in which both sequence types are common and contain the same component phonemes. Three questions were addressed: First, what is the time course of acquisition of SSP-obeying (but perceptually non-salient) stop-/s/ clusters versus SSP-violating (but perceptually salient) /s/-stop clusters for the Greek children whose utterances we studied; second, what error patterns are found during our subjects' acquisition of these sequences and how well can they be explained by major parameters such as sonority, frequency, and perceptual salience; and, third, is the timing pattern of /ts/ different from that of /ps/ and /ks/? Specifically, is the duration of the sibilant shorter in /ts/ than in /ps/ and /ks/ in children's productions, as well as adults?

The answers to these questions were mostly straightforward. First, we observed that the /s/-stop sequences (/sp/, /st/, /sk/) were produced with greater accuracy than the stop-/s/ sequences (/ps/, /ts/, /ks/), while there was essentially no difference in accuracy between /ts/ and the other stop-/s/ sequences /ps/ and /ks/. Specifically, the SSP-violating /s/-stop clusters were more accurate than the SSP-obeying stop-/s/ clusters, even though all of the clusters contained the same component sounds. Additionally, we found that /ts/ was not produced more accurately than the clusters /ps/ and /ks/, even though affricates are assumed to have a simpler syllable structure than consonant clusters, which we would expect to lead to better production accuracy.

The time-course of /ts/ relative to the other sequences in this study may lead to the interpretation that /ts/ is not an affricate in Greek child speech, since it is acquired around the same time as the other consonant clusters. This interpretation has been proposed before by Tzakosta (2001) in a longitudinal study of a Greek 2-year-old. The low production accuracy of Greek /ts/ relative to the other sequences could also imply that the suggested implicational relationship between singletons, affricates, and consonant clusters does not hold true. Even though Greek children produce singletons before more complex articulations, as we would expect in terms of articulatory complexity, we do not have evidence based on our data to suggest that affricates are acquired before consonant clusters in Greek.

Another potential explanation for the discrepancy in affricate versus cluster acquisition could reflect lexical phoneme frequency effects. Specifically, the low accuracy rate for /ts/ may be related to its low frequency of occurrence in the Greek language. Previous research has shown a positive correlation between lexical phoneme frequency and phoneme acquisition (e.g., Edwards, & Beckman, 2008; Nicolaidis, et al., 2003). To test the possibility that frequency plays a role in affricate and cluster acquisition, we examined the frequency of the target sequences in a large online adult lexicon of the most frequent 20,000 words (lemmas) in the ILSP database (Hatzigeorgiu, et al., 1999; see also Nicolaidis, et al., 2003). There were striking differences in the total number of words of the different sequence types, ranging from 221 words for /st/ to just 35 words for /ts/. Thus, it is possible that higher-frequency sequences (such as /st/) were more accurate than lower-frequency sequences (such as /ts/) because children had heard and produced more words containing them.

Observation of the frequencies of the other sequences may, however, cast doubt on this explanation, since /sp/ clusters are also very low in frequency, occurring in only 45 words of the ILSP database. If the frequency of a particular cluster type in the ambient language influences production accuracy, we would expect accuracy on initial /sp/ clusters to be rather low. However, our results show that children were in fact very accurate at producing /sp/ clusters. Thus, the frequency of individual clusters in Greek did not reliably predict the accuracy with which these clusters were produced.

Second, we found that error patterns differed in both the /s/-stop versus the stop-/s/ clusters, as well as in /ts/ versus /ps/ and /ks/. In particular, /s/-stop clusters and /ts/ were almost always reduced to a stop, in agreement with acquisition data reported for English, whereas errors for the stop-/s/clusters /ps/ and /ks/ were more variable and often involved reduction to a fricative. This is unlike what we would expect based on the SH, which predicts that the stop should have been retained.

This is not the first report of such a reduction pattern observed for initial stop-/s/ sequences. Ohala (1999) also found that when young English-speaking children reduced "non-native" clusters, including word-initial stop-/s/ clusters, they favored the production of fricatives (80%) more often than stops (9%). This reduction pattern was attributed to children's misunderstanding of this non-native cluster type (e.g., [tfuk] was interpreted as [təˈfuk]). The frequently observed process of weak syllable deletion in English was assumed to account for the later reduction of such forms to the second syllable (e.g., [fuk]).

A possible explanation for this reduction pattern in the Greek data is that it it is motivated by perceptual salience: A stop released into a fricative is more vulnerable to masking and, therefore, more susceptible to deletion than when it is released into a vowel. This is in line with the analysis proposed by Wright (2004). It is also consistent with the results of Vanderweide (2005), who found that Dutch-acquiring children first acquired segments that were more perceptible in a particular context before they acquired those that were less perceptible in that context, while they tended to reduce a cluster of the form C_1C_2V to the CV that was more perceptible. Variation in order of acquisition and reduction patterns correlated with the level of distinctness between the consonants in a given cluster. In general, consonants that were more similar to adjacent segments were more likely to delete or display variable acquisition/reduction than consonants that were more contrastive. Further research on perception of both sequence types by Greek-speaking adults is needed to confirm the hypothesis that stops in stop-/s/ sequences are indeed less perceptible than stops in /s/-stop sequences. In addition, this perceptually-based explanation does not account for the error patterns observed for /ts/, i.e., reduction to a stop. These findings also point towards a differentiated nature of /ts/ relative to /ps/ and /ks/, which merits further investigation.

Finally, we found evidence that the fine-phonetic detail of shorter [s] duration for /ts/ reported in previous studies for Greek adults (e.g., Arvaniti, 1987; Fourakis, et al., 2002) was present in the children, as well. In other words, /ts/ showed a distinct behavior relative to the other stop-/s/ sequences in terms of both its fricative duration and error patterns. Moreover, this temporal difference was not observed for the corresponding homorganic /s/-stop sequence /st/ relative to the non-homorganic /sp/ and /sk/, suggesting that homorganicity alone cannot explain the unique patterning of /ts/.

In general, our fricative duration measurements were strikingly similar for both children and adults, although children's productions were generally longer, in accordance with reports from previous studies of children's segment durations (e.g., Kent, 1980). Interestingly, however, our results show that Greek-acquiring children as young as three years mirror the adult pattern of (1) having distinct fricative durations for /s/-stop versus stop-/s/ sequences, and (2) having the shortest fricative duration for /ts/ relative to any other sequence. This implies that Greek children are treating /ts/ distinctly from very early on by using the fine phonetic cues that are available in the acoustic signal, as well as possibly differentiated articulatory patterns.

In conclusion, this study has investigated the acquisition of SSP-obeying stop-/s/ clusters (including the affricate /ts/), and SSP-violating /s/-stop clusters in Greek. The results of the study show that children are more accurate at producing initial /s/-stop clusters. This suggests that these particular clusters are easier to produce and perceive. Appealing to sonority arguments alone cannot account for this result. The SSP predicts earlier mastery of initial stop-/s/ clusters. However, this is not what we found.

An account of sonority based on perceptual salience better explains this finding. Such an account predicts that initial /s/-stop clusters are easier for children to produce because they provide a richer environment for stop place perception than stop-/s/ clusters in the same position. Perceptually more salient clusters are also predicted to show more stable error patterns. This is consistent with our findings, since errors for /s/-stop clusters primarily involved stop substitutions. On the contrary, errors for the perceptually non-salient stop-/s/ clusters were considerably more variable and often involved fricative substitutions, as well as plosive and stop-fricative substitutions. However, the perceptual salience explanation cannot account for the error patterns observed in the case of /ts/, which patterned together with those for the /s/-stop clusters and involved primarily stop substitutions.

Frequency accounts were also not satisfactory to explain our results. A frequency-based explanation predicts that accuracy should increase as frequency increases. Although performance on high-frequency sequences, such as /st/, was generally good and performance on the low-frequency /ts/ was generally poor, initial /sp/ clusters, which are low in frequency, were produced with much higher accuracy than the higher-frequency /ks/ and /ps/ clusters in contradiction to a frequency-based account.

Future research will focus on a finer-grained acoustic analysis of children's productions, to supplement our transcription data. We also plan to conduct a perception experiment to evaluate the perceptual robustness of /s/-stop relative to stop-/s/ sequences with regard to stop place of articulation. These analyses are currently underway.

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APPENDIX
List of Stimuli

Target C or CC	Vowel /a/	Vowel /e/	Vowel /i/	Vowel /o/	Vowel /u/
/p/	πάστα ['pasta] (type of pastry)	πέτρα ['petɾa] (stone)	πίνει ['pini] (he/she/it is drinking)	πόδι ['poði] (foot)	πούπουλο ['pupulo] (feather)
/t/	ταύρος ['tavɾos] (bull)	τέρας ['teɾas] (monster)	τίγρης ['tiɣɾis] (tiger)	τόξο ['tokso] (bow)	τούμπα ['tu^{m}ba] (somersault)
	τάξη ['taksi] (classroom)	τέσσερα ['teseɾa] (four)	τοίχος ['tixos] (wall)	τόνος ['tonos] (tuna)	τούρτα ['tuɾta] (cake)
/k/, [c]	κάρτα ['kaɾta] (card)	κέντρο ['ce^{n}dɾo] (center)	κήπος ['cipos] (garden)	κόκκινο ['kocino] (red)	κούνια ['kuɲa] (swing)
	κάστρο ['kastɾo] (castle)	κέρατο ['ceɾato] (horn)	κύμα ['cima] (wave)	κόκκαλο ['kokalo] (bone)	κούκλα ['kukla] (doll)
/s/	σαύρα ['savɾa] (lizard)	σέλα ['sela] (saddle)	σίδερο ['siðeɾo] (iron)	σόδα ['soða] (soda water)	σούπα ['supa] (soup)
	σάλια ['saʎa] (spit, noun)	σέρνει ['seɾni] (he/she/it is dragging)	σύννεφο ['sinefo] (cloud)	σώμα ['soma] (body)	σούβλα ['suvla] (roasting-jack)
/sp/	σπάγγος ['spaŋgos] (string)	σπέρνει ['speɾni] (he/she/it is sowing, spreading)	σπίτι ['spiti] (house)	σπόρια ['spoɾʝa] (seeds)	Not elicited
/st/	στάση ['stasi] (bus stop)	στέκεται ['stecete] (he/she/it is standing)	στύβει ['stivi] (he/she/it is squeezing)	στόμα ['stoma] (mouth)	στούπωμα ['stupoma] (bottle stopper, cork)
/sk/, [sc]	σκάλα ['skala]	σκεύος ['scevos]	σκύλος ['scilos]	σκόρδο ['skoɾðo]	σκούπα ['skupa]

	(staircase)	(utensil)	(dog)	(garlic)	(broom)
/ps/	ψάρι ['psaɾi] (fish)	ψέλνει ['pselni] (he/she is chanting)	ψίχα ['psixa] (inside part of bread)	ψώνια ['psoɲa] (groceries)	Not elicited
/ts/	τσάντα ['tsa^{n}da] (bag)	τσέπη ['tsepi] (pocket)	τσίμπλα ['tsi^{m}bla] (sticky eye discharge)	τσόφλι ['tsofli] (egg shell)	τσούχτρα ['tsuxtɾa] (jelly fish)
	τσάι ['tsai] (tea)		τσίσα ['tsisa] (baby word for peeing)		τσούζει ['tsuzi] (stinging)
/ks/	ξάδερφος ['ksaðeɾfos] (male cousin)	ξένος ['ksenos] (stranger, foreigner)	ξύλο ['ksilo] (stick, noun)	ξόπλατο ['ksoplato] (backless dress)	Not elicited

Table 1
Number of words that begin with each of the consonant or consonant sequence included in the cross-sectional study

Consonant or Consonant Sequence	Frequencies (Num of words)
/p/	1391
/t/	540
/k/, [c]	1356
/s/	1132
/sp/	43
/st/	221
/sk/, [sc]	105
/ps/	87
/ts/	35
/ks/	111

Table 2
Demographic information for child participants

Age group	Total number of boys/girls	Mean age in months (age range in parentheses)	Mean CMMS standard score (standard deviation in parentheses)
2-year-olds	7/8	30 (24-35)	N/A
3-year-olds	7/8	43 (39-48)	117* (6.3)
4-year-olds	8/7	56 (49-60)	107 (5.6)
5-year-olds	8/7	66 (61-72)	106 (8.5)

*Calculated only using the 7 children over age 3;6, because the *Columbia Mental Maturity Scale* is normed only for children aged 3;6 and older.

Table 3
Error categories for substitution errors

Error type	Description	Example
stop-fricative substitution	Production of a stop consonant followed by a fricative	['kselni] for /'pselni/ (he/she/it is chanting)
fricative-stop substitution	Production of a fricative consonant followed by a stop	['skʝazefos] for /'ksaðeɾfos/ (male cousin)
affricate substitution	Production of an affricate consonant	['tsaðelfos] for /'ksaðeɾfos/ (male cousin)
stop substitution	Production of a stop consonant	['tepi] for /'tsepi/ (pocket)
fricative substitution	Production of a fricative consonant	['saɾi] for /'psaɾi/ (fish)
other	Any other category that does not fall under the above	['tsleni] for /'pselni/ (he/she/it is chanting)

Table 4

Results of hierarchical logistic regression model for production accuracy (unit-specific model). Significant *p*-values are in bold.

Coefficient for:	Estimate	Std. Error	*t*-value	*df*	*p*-value
Intercept	0.272366	0.201181	1.354	58	0.181
Sequence_sp	0.628851	0.245365	2.563	1748	**0.011**
Sequence_st	0.493928	0.227120	2.175	1748	**0.030**
Sequence_sk	0.620322	0.227452	2.727	1748	**0.007**
Sequence_ps	0.063107	0.237951	0.265	1748	0.791
Sequence_ks	0.086433	0.238042	0.363	1748	0.716
Age (months)	0.150684	0.012496	12.059	58	**<0.001**
Variances	Estimate	Std. deviation	*df*	Chi-square	*p*-value
Intercept	1.17559	1.08425	58	268.37708	**<0.001**

Table 5
Results of hierarchical logistic regression model for error analysis (unit-specific model). Significant *p*-values are in bold.

Coefficient for:	Estimate	Std. Error	*t*-value	*df*	*p*-value
Intercept	0.355577	0.321454	1.106	28	0.279
Sequence_sp	0.189652	0.348875	0.544	607	0.586
Sequence_st	-0.566605	0.322060	-1.759	607	0.079
Sequence_sk	-0.461528	0.309281	-1.492	607	0.136
Sequence_ps	-2.410906	0.363663	-6.630	607	**<0.001**
Sequence_ks	-1.554742	0.331300	-4.693	607	**<0.001**
Age (months)	-0.076133	0.040040	-1.901	28	0.067
Variances	Estimate	Std. deviation	*df*	Chi-square	*p*-value
Intercept	1.87120	1.36792	28	187.88883	**<0.001**

Table 6
Results of hierarchical linear regression model for duration analysis (unit-specific model). Significant *p*-values are in bold.

Coefficient for:	Estimate	Std. Error	*t*-value	*df*	*p*-value
Intercept	1.942562	0.014725	131.921	45	**<0.001**
Sequence_sp	0.185633	0.011351	16.354	1138	**<0.001**
Sequence_st	0.204011	0.011532	17.690	1138	**<0.001**
Sequence_sk	0.214570	0.011312	18.969	1138	**<0.001**
Sequence_ps	0.281075	0.011576	24.280	1138	**<0.001**
Sequence_ks	0.281436	0.011536	24.396	1138	**<0.001**
Age (adult/child)	-0.080343	0.023397	-3.434	45	**0.002**
Variances	Estimate	Std. deviation	*df*	Chi-square	*p*-value
Intercept	0.00504	0.07099	45	442.91043	**<0.001**
Level-1, R	0.01381	0.11752			

FIGURE CAPTIONS

Figure 1. Percent correct productions of 10 consonant or consonant sequence types, by age group. NOTE: We merged [c] (the allophone of /k/ before front vowels) with [k] (the allophone of /k/ before back vowels).

Figure 2. Mean percent correct productions, averaged over the accuracy rates for the six sequence types /sp/, /st/, /sk/, /ps/, /ts/, /ks/, as a function of the child's age. The regression curves show the probability of correct production of the six different sequence types as estimated in the hierarchical logistic regression model described in Table 4.

Figure 3. Distribution of error types across the six sequence types in the incorrect tokens produced by 2-and 3-year-old children.

Figure 4. Percent of errors in Figure 3 that were stop errors, as a function of the child's age in months. The size of the plotting character is proportioned to the number of errors produced by the child, which ranged from 1 for the oldest of the 3-year-old boys, to 30 for a 33-month-old girl. The regression curves show the probability of a stop error for the six different sequence types as estimated in the hierarchical logistic regression model described in Table 5.

Figure 5. Median values by age group for subject-by-subject medians of the [s] durations that were input into the hierarchical linear model reported in Table 6 and of the [s] durations of singleton /s/. Boxes extend above and below the medians to indicate the interquartile ranges and whiskers extend to indicate the extreme values. The width of each box indicates the number of values—i.e., the number of subjects who had any correct tokens to contribute a (median) value to the group median.

Figure 1

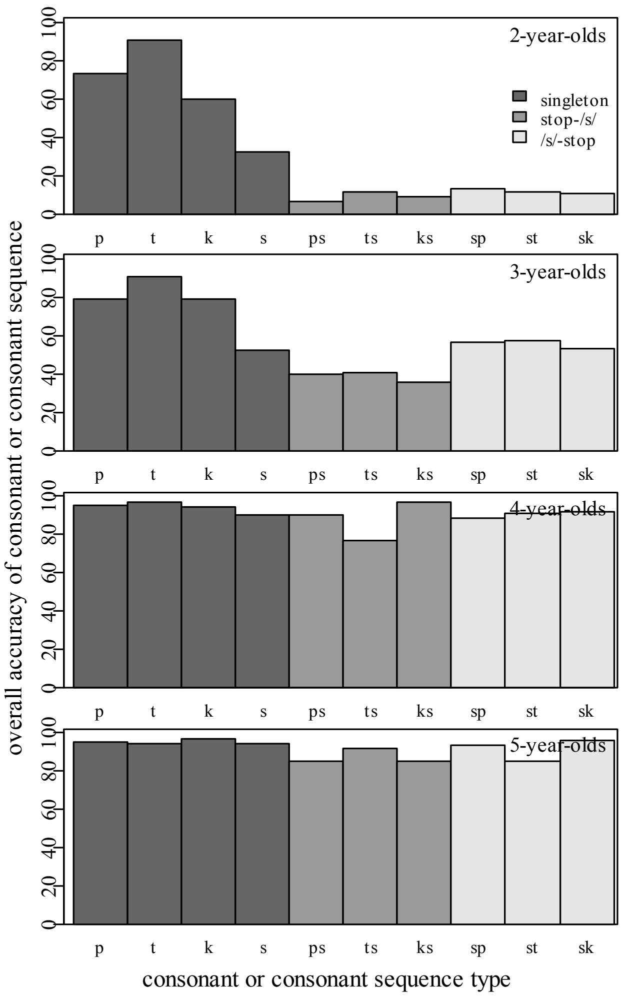

2-year-olds
singleton
stop-/s/
/s/-stop
3-year-olds
4-year-olds
5-year-olds
0 20 40 60 80 100
p t k s ps ts ks sp st sk
overall accuracy of consonant or consonant sequence
consonant or consonant sequence type

Figure 2

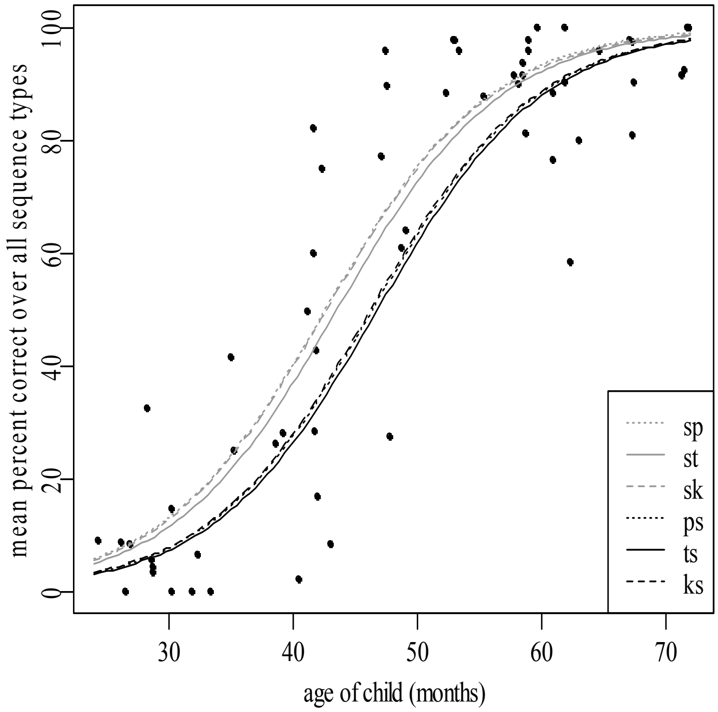

mean percent correct over all sequence types
0
20
40
60
80
100
30
40
50
60
70
age of child (months)
sp
st
sk
ps
ts
ks

Figure 3

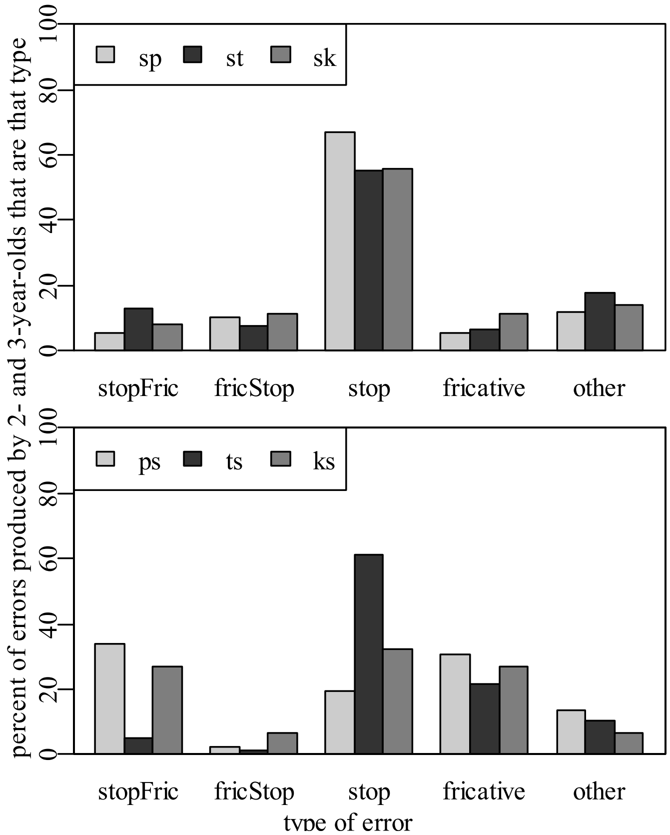

percent of errors produced by 2- and 3-year-olds that are that type
0
20
40
60
80
100
sp
st
sk
stopFric
fricStop
stop
fricative
other
ps
ts
ks
type of error

Figure 4

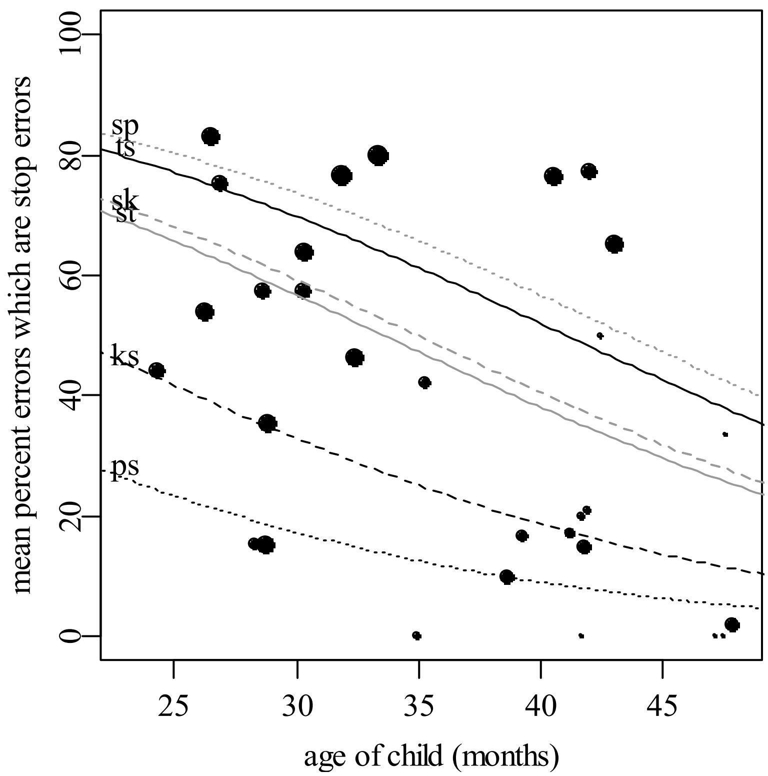
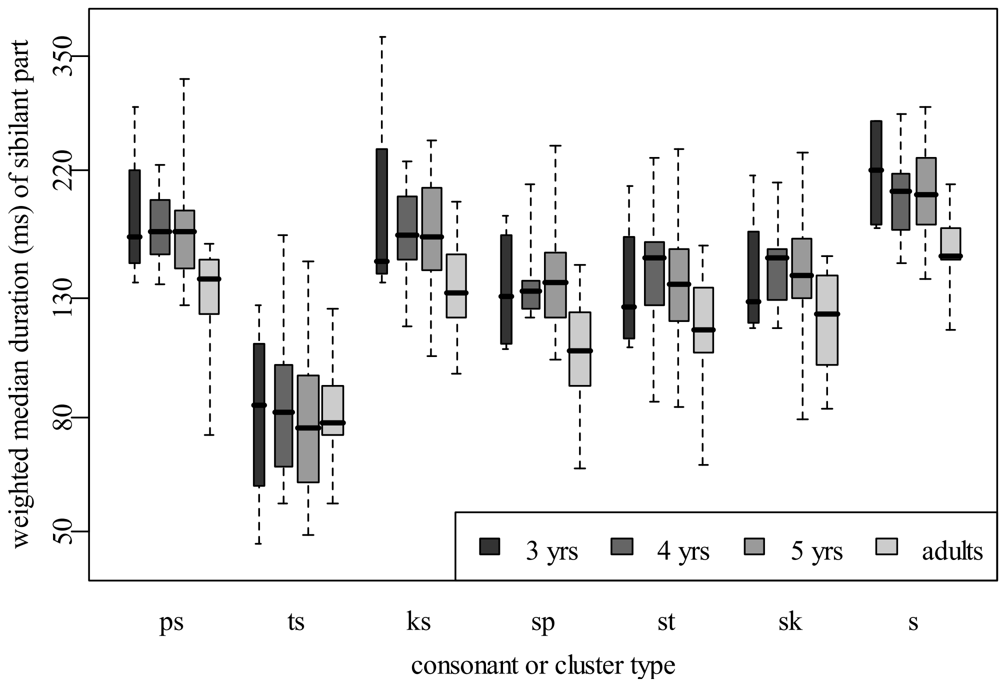

mean percent errors which are stop errors
age of child (months)
0
20
40
60
80
100
25
30
35
40
45
sp
ts
sk
st
ks
ps

Figure 5


weighted median duration (ms) of sibilant part
350
220
130
80
50
3 yrs
4 yrs
5 yrs
adults
ps
ts
ks
sp
st
sk
s
consonant or cluster type