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Cluster Development and the Veiled Rise in Sonority

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Abstract: Children's consonant cluster productions in typical and atypical phonological development were investigated for different languages reporting developmental productions that are universal, language-specific, and/or child-specific. These patterns are often interpreted considering sonority hierarchy effects. Quantitative norms on developmental cluster productions are less prevalent in the literature cross-linguistically, as are investigations on the development of less frequent cluster types in the world's languages, like those involving falling and level sonority two-member onsets. Our study contributes to these investigations, focusing on Greek-specific onsets: falling sonority obstruents [ft, xt], level sonority obstruents [fθ, fç, ðɟ, xθ, ɣð], and level sonority nasals [mɲ]. We present cross-sectional, longitudinal data from 90 monolingual children, aged 2;0–4;0, based on the word elicitation task, Phonological Assessment for Greek (PAel). As only [ft] 89%, [fç] 80%, [mɲ] 88% are acquired by 3;6–4;0, the data provide evidence that [ft, xt, fθ, xθ, ɣð] reduce to C2, [mɲ] reduces to C1, and [fç], [ðɟ] show the most variability in reduction/simplification patterns. Reduction patterns largely reflect individual cluster acquisition paths longitudinally; the relative reduction to a member changes with age, but the preference to the member does not, except for [ðɟ]. The data facilitate the establishment of quantitative markers for cluster development and qualitative interpretations in terms of featural and structural prominence, including a veiled sonority effect not previously reported in the literature.

Keywords: clusters; simplification; production patterns; falling and level sonority; Greek

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1. Introduction

Phonological acquisition is a crucial aspect of language development, encompassing how children learn and produce sounds in their native language. From around 2 years of age, children begin producing consonant clusters, with two or even three consonants together (McLeod et al., 2001a). Research findings indicate that 2-year-olds may be capable of producing a range of consonant clusters in both word-initial and word-final positions. Nevertheless, almost all children face challenges in producing these clusters correctly, with few of the younger participants achieving accurate production (McLeod et al., 2001a, 2001b).

Typically developing children, as well as those with phonological disorders, often simplify consonant clusters in their speech. By ages 1;6 to 2;5, 73% of typically developing children were observed to use cluster reduction in conversational speech (Preisser et al., 1988). Non-adult productions of consonant clusters frequently involve the omission or modification of one of the consonant elements, with processes such as reduction, simplification, and coalescence being commonly observed.

- **Cluster reduction** refers to the deletion of one or more consonants from a target cluster, resulting in a single consonant occurring at syllable margins (Grunwell, 1987). In clusters with three elements, either one or two consonants may be present at syllable margins. Cluster reduction is commonly observed in the speech of typically developing children (e.g., Dodd, 1995; Dyson & Paden, 1983; Watson & Scukanec, 1997).
- **Cluster simplification** occurs when two elements of a cluster are produced, but one or both elements undergo phonological modifications while maintaining the cluster structure. This process typically involves segmental changes, such as gliding, stopping, or fronting, as well as structural modifications like metathesis. Watson and Scukanec (1997) found that in typically developing children aged 2;0–3;0 years, cluster simplification initially increased and then declined, with the rise in simplification coinciding with a decrease in cluster reduction; as children reduce instances of cluster reduction, they tend to exhibit more instances of cluster simplification. This highlights the importance of acquiring both the correct number of elements in a cluster and refining their articulation as well as the role of different phonological repair strategies in early speech development (McLeod et al., 2001a).
- **Coalescence** occurs when a cluster is replaced by a new consonant that combines features from the original consonants. For example, the word *swim* /swɪm/ may be produced as [fɪm], where the [f] combines the [+ fricative] feature of /s/ with the [+ labial] feature of /w/. This process was observed in the speech of children aged 2 to 3 years (Dyson & Paden, 1983).

Researchers have identified a number of universal patterns in these simplifications. Consonant clusters are frequently reduced to singleton consonants by omitting either the first consonant (C1) (e.g., *smoke* [moʊk]), or the second consonant (C2) (e.g., smoke [soʊk]), or by substituting a non-target consonant (e.g., *smoke* [θoʊk]) (Barlow, 2001; Chin & Dinnsen, 1992; McLeod et al., 1997; Wyllie-Smith et al., 2006). Understanding these patterns not only enhances theoretical models of language acquisition but also has practical implications for clinical interventions.

The description of phonological acquisition focusing solely on the achievement of correct articulation may obscure the developmental stages children undergo. Developmental norms that offer only a broad outline of the acquisition process, without describing the gradual changes, fail to capture the nuances of phonological development (Elbert, 1984). An alternative approach is to examine the developmental sequence that children follow to master consonant clusters (Hutcheson, 1968).

The present study aims to investigate the acquisition of falling and level sonority clusters in Greek through a detailed analysis of developmental cluster productions. Employing a cross-sectional design, the study examines the development of two-member onsets in Greek-speaking children aged between two and four years, seeking to comprehensively document developmental production patterns within this critical age range.

1.1. Theoretical Foundations of the Study

Children's phonological development, particularly as regards cluster reduction (Greenlee, 1974; Ingram, 1989), reveals a coherent yet complex pattern in the omission of consonants. D. Ohala (1999) examined typical patterns of reduction in word-initial clusters, citing examples adapted from Locke (1983, pp. 68–71). Reduction in consonant clusters in child speech may be manifested as a reduction of the following:

- Fricative–stop clusters to stops (e.g., [pun] for *spoon*, [taɹ] for *star*).
- Stop–liquid clusters to stops (e.g., [bu] for *blue*, [ten] for *train*).
- Fricative–liquid clusters to fricatives (e.g., [faɪ] for *fly*, [sip] for *sleep*).
- Stop–glide clusters to stops (e.g., [kin] for *queen*, [butɪfəl] for *beautiful*).

- Fricative–glide clusters to fricatives (e.g., [sɪʔ] for *swing*, [sɪm] for *swim*).
- Nasal–glide clusters to nasals (e.g., [muzɪk] for *music*).

Based on these patterns, it can be proposed that cluster reduction is not a random phenomenon. However, the explanation of what drives consonant omission in clusters is complicated; children do not omit consonants based solely on their order in a cluster or due to a preference for a certain manner or place of articulation. For this reason, D. Ohala (1999) proposed that sonority-related explanations at the syllable level (Clements, 1990b) provides a more comprehensive framework, classifying segments in a syllable relative to each other in terms of language phonotactics and syllable well formedness. So, sonority is often implicated to explain cluster developmental patterns cross-linguistically as we discuss next.

1.2. Sonority Theory

Sonority refers to the degree of openness or "sound" quality in a consonant or vowel (Roca & Johnson, 1999) and is often described as a sound's "loudness relative to that of other sounds with the same length, stress, and pitch" (Ladefoged, 1975, p. 221). The degree of sonority is closely linked to the extent of vocal tract constriction during sound production, with more sonorous segments resulting from greater vocal tract openness. Vowels are considered the most sonorant segments of the syllable, followed by glides, liquids, nasals, and obstruents, in decreasing order of sonority (Hooper, 1976; Selkirk, 1984). Among these classes, there are further distinctions, such as voiceless consonants are less sonorous than voiced consonants and high or mid vowels are less sonorous the high vowels (e.g., Blevins, 1995; Clements, 1990b). Steriade (1990) introduced a numerical sonority hierarchy that ranks phonemes from most to least sonorous, corresponding to the degree of vocal tract constriction: 0—vowels; 1—glides; 2—liquids; 3—nasals; 4—voiced fricatives; 5—voiceless fricatives; 6—voiced stops; and 7—voiceless stops. Although there is consensus on the perceptual aspects of sonority, it has not been directly correlated with acoustic measures of speech (Klopfenstein & Ball, 2010). Sonority is, thus, used to evaluate whether or not groups of segments behave similarly cross-linguistically when the same processes are involved (Parker, 2012). In spite of ongoing debate on the extent to which sonority can explain developmental variability in productions (e.g., Ball & Müller, 2016; Yavaş & Babatsouli, 2016), the concept of sonority has been influential in explaining various phenomena related to syllable phonotactics and well-formedness cross-linguistically (e.g., Kenstowicz, 1994), but also to investigate children's consonant cluster production in both typically developing children (e.g., Barlow, 2001; McLeod & Crowe, 2018) and those with phonological impairments (Chin, 1996; Gierut, 1998, 1999; Gierut & Champion, 2001).

According to the sonority sequencing principle (SSP), a segment constituting a sonority peak in a syllable nucleus is preceded and/or followed by segment(s) with progressively decreasing sonority values (Clements, 1990b; Blevins, 1995; Hooper, 1976; J. J. Ohala, 1990a, 1990b; Selkirk, 1984). Tautosyllabic cluster inventories across languages differ in this respect because languages may have different phonotactic requirements in terms of the minimum sonority distance, defined as a minimum number of ranks on the sonority scale that languages utilize to determine permitted members in tautosyllabic clusters (Selkirk, 1984; Steriade, 1982). Overall, an increase in sonority distance between members means that the cluster is more complex/marked, and thus more difficult to acquire. Clusters with falling/negative sonority (e.g., skate /skeɪt/) are more marked than level sonority clusters (e.g., Hebrew /ptitʃa/ "opening") which, in turn, are more marked than rising sonority clusters (e.g., *blue* [blu]) (see Yavaş & Babatsouli, 2016). Among rising sonority clusters, those with a smaller sonority distance (e.g., /fl/ in *fly*) are more complex than those with a greater difference, e.g., /pj/ (e.g., *pure*). Syllable structures with least marked sonority sequences will tend to be acquired earlier in development than those with more marked sequences (Clements, 1990a, 1990b). D. Ohala (1999) further argued that sonority "… predicts differential production of the same consonant depending on the type of cluster within which the consonant is contained" (p. 402). For example, in an initial fricative–stop cluster, the fricative [s] is predicted to be omitted (e.g., *stake* becomes [tek]), whereas in an initial Fricative + Nasal cluster, it is predicted to be retained (e.g., *snake* remains [sek]). Overall, sonority-related explanations offer specific predictions about consonant reductions in children's speech, particularly focusing on the interactions between cluster type, consonant preservation, and syllable position. Barlow (2016) provides a comprehensive review on the topic.

1.3. Cross-Linguistic Studies on Cluster Acquisition and Cluster Reduction

1.3.1. Studies on Typically Developing Children

Building on Locke's (1983) initial observations of consonant patterns, D. Ohala (1999) conducted two studies on consonant cluster reduction in 16 typically developing English-speaking children aged 1;9–3;2 years. The studies employed 28 monosyllabic nonsense words to represent 7 different cluster types, with 4 nonsense words for each cluster. These items featured either a syllable-initial cluster (CCVC) or a syllable-final cluster (CVCC) and were designed so that no reduction in the cluster would produce a real word. In the first study, the clusters included those found in English, while the second study used consonant clusters that were not possible in English, though some were phonologically similar to clusters that do occur in the language. Both studies tested a hypothesis derived from sonority-related explanations, which posits that children reduce clusters to the consonant that results in the least complex syllable according to sonority principles. The hypothesis was, that for initial clusters, children would retain the consonant that produced the most significant rise in sonority, whereas for final clusters, they would retain the consonant that maintained a minimal descent in sonority. In both studies, children heard the experimenter produce the nonsense words, attributed to a "funny" or "silly" animal, and were asked to repeat the name of the new animal. The results indicated that when children reduced initial Fricative + Stop clusters (e.g., st-, sk-) and initial Fricative + Nasal clusters (e.g., sn-), the retained consonant in the word onset position was the less sonorous element. Additionally, when children reduced Fricative + Stop clusters (e.g., -st) in word-final position, the consonant retained in the coda was the most sonorous. The analysis revealed no main effects of either cluster position or consonant type, but there was an interaction between these two factors that aligned with the predictions of sonority theory. Overall, the results from both studies supported this sonority-based explanation of cluster reduction.

In a subsequent study, Wyllie-Smith et al. (2006) analyzed the production of consonant clusters in word-initial positions in a group of 16 typically developing English-speaking children. They found that cluster reduction occurred in 37.1% of the target word realizations. The proportion of these reductions that adhered to the sonority hierarchy (SH) was also calculated. Results indicated that 88.2% of the target cluster reductions followed the SH. Further analysis of the reduced clusters within the four consonant cluster categories revealed that the majority of Fricative + Nasal (+80%), Fricative + Glide (+100%), and Stop + Liquid (+100%) clusters were reduced to the least sonorous element, thus adhering to the SH. However, reductions in the Fricative + Stop clusters showed an almost equal number of reductions to the most and least sonorous elements, with 54% of the realizations adhering to the SH.

Further research by Levelt et al. (2000) in a longitudinal study of syllable structure acquisition in twelve Dutch-speaking children aged 1;0 to 1;11 revealed variability in the development of word-initial versus word-final consonant clusters. The study found that nine children produced word-initial CCVC clusters first, while three children initially produced word-final CVCC clusters. Levelt et al. (2000) suggested that this developmental pattern might be influenced by the fact that initial and final clusters occur with equal frequency in Dutch. However, when frequency was not a factor, the majority of Dutch-speaking children tended to produce consonant clusters in the initial position before the final position, indicating that markedness factors may have influenced their performance.

Similarly, Demuth and McCullough (2009) found that French-speaking children acquire complex syllable structures initially at the beginning of words rather than at the end. Their study analyzed spontaneous speech productions from two typically developing French-speaking children aged 1;5 to 3;0 during child–parent interactions. This age range was selected due to the sufficient number of target words with consonant clusters available. The study specifically examined the acquisition of obstruent-/R/ (OR) and /R/-obstruent (RO) clusters, as these were adequately represented in the corpus. The findings indicate that clusters in the onset position are acquired earlier than those in the coda, even when controlling for sonority factors.

By the age of two, Finnish-speaking children are typically able to produce certain heterosyllabic consonant clusters, such as the homorganic clusters /mp/, /nt/, and /ŋk/, where both consonants share the same place of articulation. However, even children with nearly complete consonant inventories may not necessarily be able to produce clusters, suggesting that there may be specific production constraints related to clusters (Saaristo-Helin et al., 2011). Further evidence from Saaristo-Helin’s (2009) study shows that at age 3;0, Finnish-speaking children correctly produced an average of 83% of targeted clusters, and by age 3;6, their accuracy improved to 91%. This finding highlights that while Finnish-speaking children as young as 2;0 can produce specific heterosyllabic clusters, particularly homorganic ones, the ability to produce other clusters may still present challenges, even for older children with nearly complete consonant inventories. Indeed, the fact that the phonetic inventory for the production of all consonants in a language has been completed for a child does not necessarily mean that the child is capable of producing all possible consonant combinations or mastering the phonotactic structure of consonant clusters. The production of consonant clusters may pose greater demands than the ability to produce individual consonants.

Kirk and Demuth (2005) conducted a cross-sectional study involving twelve English-speaking two-year-olds (aged 1;5–2;7) to examine the production of consonant clusters. They found that the children were more accurate at producing word-final obstruent + /s/ clusters (e.g., *cups*) compared to word-initial /s/ + obstruent clusters (e.g., *spoon*). However, the children struggled with word-final clusters that had the same segments in reverse order (e.g., *wasp*), often metathesizing them (e.g., *waps*). These findings suggested that the higher frequency of word-final obstruent + /s/ sequences in English, many of which were inflectional morphemes (e.g., *socks*), may have facilitated their earlier acquisition. In contrast, less frequent monomorphemic clusters, such as in *box*, were more challenging for children to produce correctly. This indicated that both input frequency and morphological status significantly influenced the development of consonant clusters in young children. In a subsequent study, Kirk (2008) investigated the production of consonant clusters in 11 typically developing monolingual English-speaking children aged 1;5 to 2;7 years. The study explored whether cluster substitutions could be predicted from the errors children make with the corresponding singletons. Consonant clusters in both word-initial and word-final positions were elicited using a picture identification task. The findings revealed that nearly one-third of cluster substitutions could not be predicted from the errors on the corresponding singletons. Furthermore, most of these unpredictable substitutions involved clusters where both consonants had the same place and/or manner of articulation, suggesting that about 70% of these substitutions were influenced by assimilation within the cluster.

1.3.2. Studies on Children with Phonological Impairments

Wyllie-Smith et al. (2006) investigated whether the patterns of cluster reduction observed in the speech of children with speech impairments adhered to the sonority hypothesis. The study recruited 40 Australian English-speaking children aged 3;6 to 5;8 years who were referred for speech and language assessment due to being unintelligible. These children had not received any speech and language therapy (SLT) intervention prior to the study. They were assessed using a single-word picture naming task that included 21 words containing word-initial clusters. The results indicated that cluster reduction occurred in 30.3% of the realizations. A detailed analysis showed that, among these cluster reductions, the first consonant was retained in 8.4% of the reductions, the second consonant in 10%, and a non-target consonant appeared in 11.9% of the reductions. Overall, 54% of the observed reductions adhered to the sonority hypothesis. Regarding the profiles of the participating children, out of the 37 participants who did reduce clusters, only 7 consistently adhered to the sonority hypothesis, while the majority—30 children—did not, showing a significant difference between those adhering to and those violating the SH.

Klopfenstein and Ball (2010) present the case of a 4-year-old American English-speaking child with unintelligible speech, whose cluster realizations did not always follow the sonority hypothesis. The participant reduced several clusters in both onset and coda positions as predicted by the SH (18 clusters). However, cluster realizations that violated the SH were also observed (10 clusters), suggesting that sonority principles do not fully account for all cluster reductions in the disordered speech of this case study.

Gierut and Champion (2001) conducted an intervention study involving eight children with functional phonological delays, targeting word-initial three-element clusters. The study aimed to determine whether addressing these complex clusters would facilitate phonological learning and affect the acquisition of related but simpler structures, such as singletons, affricates, and two-element clusters. The results indicated that while the children learned the treated three-element clusters, there was no significant generalization to similar types of (asymmetric) onsets. However, the treatment resulted in widespread generalization to untreated singletons, including affricates. Differential generalization to untreated two-element clusters was observed, with individual variations related to each child’s singleton inventory. These findings suggest that non-linear considerations (both segmental and prosodic (syllable) units) may provide predictive insights for evaluating the effectiveness of clinical treatments based on linguistic complexity.

In summary, cross-linguistic studies on consonant cluster acquisition show that typically developing children often simplify consonant clusters, frequently adhering to sonority-related principles. The acquisition of consonant cluster production generally follows a developmental sequence, with simpler structures being acquired before more complex ones. Children with phonological impairments exhibit varied patterns in cluster reduction, also subject to sonority-related effects. These findings highlight the importance of understanding developmental patterns and phonological processes to inform effective intervention. However, specific data on the acquisition of consonant clusters and developmental trajectories in Greek are limited. There is a clear need for further research, particularly to examine how Greek-speaking children acquire clusters, especially those not investigated previously or that are typologically under-represented cross-linguistically. Such research could provide valuable insights into the typical developmental trajectory for Greek-speaking children and aid in the development of targeted intervention strategies for those with phonological delays. In the following section, the phonological system of Greek will be presented, along with a review of studies on Greek-speaking children, to establish the context for the study.

1.4. The Greek Language

To provide a clearer context for the study, a brief overview of the Greek phonological system is essential. Greek has five vowels /ɐ, ɛ, i, o, u/ and a rich inventory of consonant phonemes and allophones. The consonants include voiceless and voiced plosives /p, b, t, d, k, g/ and fricatives /f, v, θ, ð, s, z, x, ɣ/. Additionally, Greek features nasals /m, n/, liquids /ɾ, l/, and a glide /j/. Greek has palatal allophones [c, ɟ, ç, ʝ, ɲ, ʎ], which are derived from respective /k, ɡ, x, ɣ, n, l/ in the context of following /i/, /iV/ or /e/ (Arvaniti, 1999). Voiceless plosives are unaspirated, and voiced plosives are fully prevoiced (Mennen & Okalidou, 2007). Greek distinguishes between voiced and voiceless palatal and velar fricatives, and also uses interdental fricatives (Ladefoged, 2001). Consonants are permissible in syllable-initial, word-initial, and medial positions. However, only a few consonants (/ɾ, l, θ, n/) appear in syllable-final, word-medial positions, and only /s, n/ are used in syllable-final, word-final positions (Mennen & Okalidou, 2007). Greek exhibits "dynamic" stress, where stressed syllables are generally longer and/or have higher amplitude compared to unstressed syllables (Arvaniti, 1999). The syllable structure in Greek may be represented by the formula $C_{(0\text{-}3)}VC_{(0\text{-}1)}$ (Mennen & Okalidou, 2007) (for other reports, see, e.g., Holton et al., 2015; Kappa, 2002; Nikolopoulos et al., 2006; Setatos, 1974). Topintzi and Baltazani (2016) investigated the morphophonology of Greek /j/ in prevocalic position arguing for the glide's dual nature as both a distinct phoneme /j/ and an allophone of /i/. Setatos (1974) shows /i/ in the representation of Greek syllables underlyingly (e.g., CiV, CCiV, etc.), /i/ being part of a branching nucleus. Cross-linguistically, /i/ commonly surfaces as the semi-vowel [j] in such contexts because the two segments are phonetically very close (e.g., Bernhardt & Stemberger, 1998). Whether the underlying representation of the syllable is indicated as /CiV/ or /CjV/ in Greek (Setatos, 1974; Revithiadou, 2021; Topintzi & Baltazani, 2013), /i/ or /j/ are realized as palatals [ç,], [ʝ] [ʎ] or [ɲ], in the context of such syllables, e.g., /fio~fjo/→[fço], /ðia~ðja/→[ðʝɐ], /mia~mja/→[mɲɐ], and /liɐ~ljɐ/→[ʎɐ].

The language also includes a variety of consonant clusters, such as [sk, st, sp, kɾ, tɾ, pɾ, kl, pl]. For a comprehensive list of Greek clusters in word-initial, medial-onset, and medial heterosyllabic contexts (see Babatsouli, 2019, Supplemental Material: Scan Form, pp. 6–8; Babatsouli, 2023). Greek has a preference for open syllables (e.g., Holton et al., 2015; Kappa, 2002; Nikolopoulos et al., 2006; Setatos, 1974). Most Greek words are bisyllabic or multisyllabic (Setatos, 1974), with high-frequency content words often consisting of three or more syllables. Monosyllabic nouns are less common (Aidinis & Nunes, 2001). The use of polysyllabic stems is characteristic of Greek, as seen in commonly used words such as [kɐɾɐˈmɛl-ɐ] "candy" and [poˈðilɐt-o] "bicycle", which are combined with appropriate morphemes for gender, case, and number (e.g., Holton et al., 2015). For a recent review of standard Greek speech acquisition, see Okalidou and Babatsouli (in press).

The Acquisition of Consonant Clusters by Greek-Speaking Children with Typical Development and Phonological Disorders

Cross-linguistic findings on phonological acquisition and consonant cluster development appear to be confirmed in Greek, demonstrating both common patterns and language-specific features. The acquisition of consonant clusters in typically developing Greek-speaking children follows a systematic process involving both segmental modifications (e.g., gliding, stopping) and structural changes (e.g., metathesis), with various phonological repair strategies emerging during early development. In the initial stages, Greek-speaking children were reported to simplify consonant clusters using several strategies, with cluster reduction being the most widely observed (Kappa, 2002; Tzakosta, 2003, 2009; Kappa & Papoutsi, 2019). For Obstruent + Sonorant clusters, reduction typically targets the less sonorous segment, resulting in the deletion of the obstruent and the retention of the sonorant. This pattern aligns with cross-linguistic data, and studies on Greek, such as those by Kappa (2002), Kappa and Papoutsi (2019), and Ploumidi (2020), confirm this tendency in young Greek learners. For example, words like *βιβλίο* [viˈvlio] "book" are simplified to [viˈlio], and *γλυκό* [ɣliˈko] "sweet" becomes [liˈko]. As reported by Tzakosta (2003, 2009) and Kappa (2002), a reduction in Obstruent + Sonorant clusters often results in the deletion of the obstruent, as seen in forms like *βλέπει* [vlɛpi] "see" becoming [lɛpi]. In addition to reduction, metathesis is observed as a structural modification strategy in Greek, where the second consonant of an Obstruent + Sonorant cluster shifts leftward to form the coda of the previous syllable. For example, *πούδρα* [ˈpuðɾɐ] "face powder" is realized as [ˈpuɾðɐ] (Kappa & Papoutsi, 2019). Coalescence, though less frequent, is also documented in Greek, where two consonants merge into one, combining features from both. This is seen in words like *έξι* [ˈɛksi] "six" becoming [ˈɛtii] (Kappa, 2002) or *μπλέ* [blɛ] "blue" simplified to [ˈde] (Ploumidi, 2020). Epenthesis, the insertion of a vowel between consonants, is a less common strategy for cluster simplification in Greek, yet it was observed in cases like *μπλέ* [blɛ] "blue" being realized as [bɛˈlɛ] (Kappa, 2002) or *κρύο* [kɾio] "cold" simplified to [kɐˈɾio] (Tzakosta, 2009). Regarding the acquisition order of clusters, research indicates that Greek-speaking monolinguals generally acquire Obstruent + Sonorant clusters earlier than reversed sonority clusters such as s + Obstruent (e.g., Kappa, 2002). However, studies reveal some variation in this order. For instance, Sanoudaki (2010) found that some children acquire reversed sonority clusters first, while others follow the more typical pattern. Recent work by Geronikou and Babatsouli (2024) suggests that Obstruent + Sonorant clusters like /bl/ and reversed sonority clusters like /st/ are both acquired by Greek-speaking children between the ages of 2;6 and 3;0. By the age of 4;6–5;0, children typically master both types of clusters, with no significant differences in their acquisition order.

In summary, Greek-speaking typically developing children employ several strategies, including reduction, metathesis, coalescence, and epenthesis, to simplify consonant clusters. While Obstruent + Sonorant clusters tend to be acquired earlier, there is variation in the exact order of acquisition, with recent studies showing no significant difference in the mastery of different cluster types by the age of 5 years.

Turning to Greek-speaking children with phonological disorder (PD), errors in the realization of consonant clusters tend to persist longer compared to typically developing peers. Cluster reduction is a frequently reported simplification strategy, with the less sonorous obstruent segment typically retained. This pattern is seen in Obstruent + Sonorant clusters, such as in the word *μπλούζα* ['blu.zɐ] "blouse" simplified to ['bu.zɐ], and in *γράμμα* [ˈɣɾɐ.mɐ] "letter" reduced to [ˈɣɐ.mɐ] (Tzakosta & Stavgiannoudaki, 2013; Giannakaki, 2020). Research has shown that Greek-speaking children with PD tend to master well-formed tautosyllabic two-member clusters, such as Obstruent + Sonorant, earlier than word-medial codas and s-clusters, which are typically more challenging. Tzakosta and Stavgiannoudaki (2013) provide evidence that in a group of five Greek-speaking children with Developmental Language Disorder (DLD), aged 4;06 to 5;00 years and exhibiting speech delays, utilized repair strategies similar to those used by typically developing children were employed. Different repair strategies were used depending on the type of consonant cluster. Gatsou (2022) studied cluster simplification processes in a group of 10 Greek-speaking children with phonological disorders within the context of DLD, aged 4;6 to 5;11 years (with a mean age of 5 years and 3 months). Her findings revealed that 78% of these children demonstrated accurate realizations of Obstruent + Sonorant clusters in word-initial positions, such as in the word *πλυντήριο* [pliˈdiɾio] "washing machine", and 76% realized them correctly in word-medial positions, as in *καρέκλα* [kɐˈɾɛklɐ] “chair”. However, their realization of word-medial codas was significantly lower, with only 25% of target words being produced accurately. Recently, Iliopoulou and Kappa (2024) presented the case of a Greek-speaking boy, aged 4;6 to 5;0, diagnosed with DLD and exhibiting a phonological disorder and attending speech and language therapy. The child struggled to produce well-formed Obstruent + Liquid clusters. To faithfully realize the target number of segments in a word, metathesis was employed, showing variation depending on the cluster’s position within the word. In word-medial positions, the liquid changed to the preceding syllable’s coda, while in word-initial positions, the liquid’s manner of articulation was altered, but its coronal place was preserved, resulting in the realization of a coronal sibilant [s] at the word’s left edge. Overall, while Greek-speaking children with PD exhibit similar patterns of simplification as their typically developing peers, certain challenges, particularly with word-internal codas, persist for a longer period.

In summary, there is a growing body of literature on phonological development and its disorders in Greek, including single case studies and research involving small participant samples. While these studies provide valuable insights, they often lack the comprehensive scope needed to establish robust developmental production patterns. Understanding how phonological skills, such as cluster reduction, evolve as children mature is crucial for identifying typical developmental pathways and comparing these with atypical phonological development. Therefore, a cross-sectional study was conducted to address this gap and offer a clearer picture of cluster reduction patterns and cluster development in Greek-speaking children.

1.5. The Goal of the Study

Children’s cluster reduction patterns during phonological development were investigated in the literature for different languages (see review in McLeod et al., 2001a and ref therein). Clusters with rising sonority, such as *pl*- and *tr*-, follow the sonority sequencing principle (SSP), making them more natural and typically easier for children to acquire compared to clusters with falling or plateau sonority. In Greek, these clusters tend to emerge early in development with fewer errors, as they align with the preferred rising sonority contour within syllables. This study seeks to enhance our understanding of how children’s clusters development with cross-sectional data in Greek. The focus is on two-member onsets because they are infrequent in phonotactics of languages and, as a result, under-represented in the literature on normative acquisition studies (Geronikou & Babatsouli, 2024). Specifically, our cross-sectional study examines the development of falling and level sonority two-member onsets in Greek and aims to comprehensively document developmental production patterns in children between ages 2;0–4;0.

The study focuses on this age range as children are reported to be capable of producing consonant clusters (McLeod et al., 2001a, 2001b), yet most typically developing children still experience difficulties with accurate cluster production in conversational speech (Preisser et al., 1988). Investigating cluster production and patterns of difficulty between 2;0 and 4;0 years of age in Greek-speaking children could provide valuable insights into their typical developmental trajectory. The study aims to capture the nuanced stages of phonological development that are often overlooked when focusing solely on accuracy or inaccuracy. It will examine in detail whether consonant clusters are produced correctly, reduced to singleton consonants by omitting the first (C1) or second consonant (C2), inaccurately produced due to substitution of the first or second consonant, or substituted entirely with a non-target consonant. This in-depth analysis will offer a more comprehensive understanding of the developmental pathways of consonant clusters during early childhood.

2. Materials and Methods

2.1. Study Design

A cross-sectional design was used to investigate the development of falling and level sonority two-member onsets in Greek-speaking children aged 2;0 to 4;0. The present study builds on elicited data as reported in Geronikou and Babatsouli (2024). The focus here is to provide a novel, in-depth analysis of previously reported aggregate data setting new research questions. The study aims to comprehensively document Greek-specific cluster developmental patterns not reported previously. The focus is on this age range because the data investigated are most interesting during this period. It is known that children have mostly acquired the speech sound systems of their targeted language by age 4;0 (e.g., Ingram, 1989; Ingram & Babatsouli, 2024).

2.2. Participants

Ninety Greek-speaking children participated in the study, divided into four age groups. They were randomly selected from local preschools and daycare centers in Athens, Patras, Crete, Samos, and Veria. The data collection areas were chosen purposefully including both mainland and island regions to ensure a more thorough representation of Greek-speaking children's speech production.

All children were Greek monolinguals. Demographic information of the child participants in terms of age and gender can be seen in Table 1 grouped in 6-month age intervals.

Table 1. Participants' demographic data in 6-month age intervals.

Age Group	**Gender**		**Total**
	Boys	**Girls**	
2;0–2;5	9	8	17
2;6–2;11	6	10	16
3;0–3;5	11	9	20
3;6–3;11	16	21	37
Total	42	48	90

2.3. Inclusion Criteria

To be included in the study, the children should have met the following criteria: (i) they have achieved developmental milestones as expected including both language development and general milestones such as gross and fine motor skills; (ii) they have normal speech and language skills as estimated by their teachers; and (iii) they did not have a diagnosed biomedical condition. Information was collected through parental questionnaires and school records, which included medical examinations as an entry requirement. Parental consent and child assent were gained prior to testing. Parental written consent was obtained for the study following the Declaration of Helsinki ethical procedures.

2.4. Task Description

The tool used for phonological elicitation and analysis was the Phonological Assessment for Greek (PAel) (Babatsouli, 2019). PAel is a single-word elicitation task consisting of 150 content words (mostly nouns and adjectives) divided into two parts: the Screener, which includes 50 words for preliminary/basic assessment, and the Extended list, which contains 100 additional words for evaluating more advanced phonological skills. Utilizing both lists offers a comprehensive profile representative of Greek phonotactics.

2.5. Task Administration

In the context of a broader study investigating developmental norms of phonological development in Greek, children were assessed individually in a quiet room within the school setting. Word-list data were elicited using the PAel culture-relevant color images (one per word) that are freely available in slideshow software from: http://www.phonodevelopment.sites.olt.ubc.ca. Sentence cues (cloze technique), and/or phonemic, syllabic cues, included in the slideshow for clinical use to motivate children during the test, were minimally utilized as needed. Output productions were transcribed online by the experimenter (the second author and undergraduate speech and language therapy students under her supervision). Children's speech productions were audio recorded (digital recordings on a laptop placed 50 cm away with a built-in Lenovo Audio Device were configured to 2 channels, 16-bit, 48,000 Hz; the data were stored in compressed M4A format). Recordings were used to ensure fidelity of transcriptions and were confirmed through inter-rater reliability. Each stimulus was elicited only once; if a child attempted a second correct response, this was taken for scoring. The examiner did not correct the children. One assessment session, approximately 45 min long, took place for each child. Children were allowed to complete the task at their own pace, and they were praised for participation and not for the accuracy of their answers. Stimuli of interest in the context of the present study can be seen in Section 2.6. The complete list of 150 words along with the number of instances for each cluster and their positions in the word can be found in the description of the Phonological Assessment for Greek (PAel, Babatsouli, 2019); the test procedures are freely available at the following link: https://phonodevelopment.sites.olt.ubc.ca/%CE%B5%CE%BB%CE%BB%CE%B7%CE%BD%CE%B9%CE%BA%CE%AC-greek/.

2.6. Stimuli of Interest

The study examined production patterns in two-member consonant onsets in Greek, focusing on the Greek true clusters with **falling and level sonority**, except for level sonority onset [pt]; this cluster is uncommon in children's everyday vocabulary. True clusters, unlike adjunct clusters (s-clusters), obey the SSP and are more complex prosodically in that both members are appended under the same syllable (e.g., Barlow Yavaş & Babatsouli, 2016). A falling sonority CC comprises a C1 of higher sonority (e.g., Fricative [f]) than the C2 (e.g., plosive [t]). A level sonority CC comprises a C1 of the same sonority value as the C2 (e.g., fricatives [f] and [θ], or nasals [m] and [n]). Specifically, **falling sonority obstruents** were represented by the clusters **[ft]** in *φτερά* [ftɛ.ˈɾɐ] "feathers") and **[xt]** in *χτένα* [ˈxtɛ.nɐ] "comb" and *νύχτα* [ˈni.xtɐ] "night". For **level sonority obstruents**, the clusters **[fθ]** in *φθινόπωρο* [fθiˈno.po.ɾo] "autumn", **[fç]** in *φιόγγος* [ˈfço.gos] "ribbon" and *ζωγραφιά* [zo.ɣɾɐ.ˈfçɐ] "drawing", **[ðʝ]** in *διαβάζει* [ðʝɐ.ˈvɐ.zi] "reads" and *κλειδιά* [kli.ˈðʝɐ] "keys", **[xθ]** in *χθες* [ˈxθɛs] "yesterday", **[ˈvð]** in *ραβδί* [ɾɐ.ˈvði] "stick", and **[ˈɣð]** in *γδέρνει* [ˈɣðɛɾ.ni] "scratches" were analyzed. Additionally, **level sonority nasals** were explored with the clusters **[mɲ]** in *μοιάζουν* [ˈmɲɐ.zun] "resemble" and **[mn]** in *λίμνη* [ˈli.mni] "lake". These clusters are among the most frequent ones in Greek (Protopapas et al., 2012) but are under-investigated in Greek, and unrepresented cross-linguistically. The goal was to investigate how these clusters undergo simplification or reduction during speech development to inform phonological development in Greek, and cross-linguistically, as well as clinical practices of speech assessment and intervention.

2.7. Cluster Production Patterns

Data were coded into response categories to analyze the patterns of cluster reduction and realization, as shown next.

1. **Complete Omission of Cluster**, where the cluster was entirely omitted;

2. **C1**, indicating that only the first consonant was present, either accurately produced or substituted.
3. **C2**, where only the second consonant was produced, either accurately or substituted.
4. **C**, representing cases of coalescence where one consonant retained features of both C1 and C2.
5. **C1&C2**, where both consonants were produced or substituted.
6. **Non-Specified Change**. Additionally, a category for Non-Specified Change was included for instances that did not fit neatly into the other classifications.

This coding scheme provided a comprehensive understanding of the variable cluster production patterns.

Adult-like realizations were defined as productions that followed the phonotactic structure and consonant combinations typical of adult speech in the target language. Variations reflecting dialectal differences, such as the palatalization of consonants in Western Greece, were considered acceptable and not marked as incorrect when permissible within the local dialect. This ensured that the analysis concentrated on developmental speech difficulties rather than linguistic features tied to regional or dialectal variations.

To minimize the influence of dialectal variation, productions were only scored as incorrect if a consonant was omitted or replaced with one not characteristic of the local dialect for the target consonant. For instance, features such as the palatalization of /l/ in Patras were treated as acceptable when consistent with the local dialect. Moreover, children from various regions were included in the study to achieve broad representation and generalizability.

2.8. Inter-Rater Reliability

To ensure the reliability of scoring performance, the second author transcribed all recordings in the International Phonetic Alphabet (IPA) and the first author independently conducted transcriptions in IPA for 10% of the data collected. Minimal inter-rater disagreement (less than 3%) was resolved through consensus in follow-up listening sessions.

3. Results

This section presents the results of our study in the following sections: (i) samples and two-member productions, (ii) cluster reduction patterns, (iii) cluster reduction to a single member, (iv) entropy of cluster stages, and (v) cluster reduction including omission across all ages.

3.1. Samples and Two-Member Productions

Table 2 shows the number of children in the study per age group (in the four columns on the right) and the children's two-member cluster productions (in the eight rows, one per cluster). Each of the rows has two separate lines. The top line shows a single number per age group which corresponds to the number of responses per cluster per age group. The bottom line of each row shows two numbers (percentages) per age group; the one on the left corresponds to the percentage of two-member cluster productions, while the one on the right corresponds to the percentage of adult-like cluster productions. Two-member productions include both adult-like productions and any two-member productions in which members are produced either by substituting target cluster members or by any other phonological process. More on this follows in the Section 4 below. Clusters [mɲ] and [mn] were merged into a single category, denoted with [mɲ] in Table 2, because the aggregate data show no differentiation in accuracy or developmental patterns between the two. The number of responses in the youngest age group is limited, less than one-third, in the abstract words targeting the word-initial clusters [fθ], [ðʝ], [xθ], [ɣð], and [mɲ], and this persists for [xθ] at ages [2;6–3;0). This must be considered when comparing the outcomes for each cluster within each age group and across age groups. As a result of a small sample, cluster [ɣð] appears to perform better in the youngest age group compared to even the oldest age group as far as two-member and adult-like productions are concerned, that is, (67%, 67%) versus (52%, 30%). All other clusters perform overall better with increasing age.

Table 2. Cluster samples by age group, two-member, and adult-like productions.

			Age [1]		
	cluster	[2;0–2;6) 16	[2;6–3;0) 16	[3;0–3;6) 20	[3;6–4;0) 35
row 1	ft	7 14%, 14%	10 60%, 60%	20 70%, 55%	35 91%, 89%
row 2	xt	6 17%, 17%	11 73%, 64%	20 65%, 55%	35 83%, 66%
row 3	fθ	5 0%, 0%	10 10%, 0%	20 20%, 20%	35 54%, 49%
row 4	fç	10 30%, 30%	14 50%, 50%	20 45%, 45%	35 86%, 80%
row 5	ðʝ	5 20%, 0%	9 33%, 33%	20 40%, 40%	35 54%, 51%
row 6	xθ	0 n/a, n/a	0 n/a, n/a	18 44%, 44%	35 80%, 49%
row 7	ɣð	3 67%, 67%	8 0%, 0%	17 41%, 29%	33 52%, 30%
row 8	mɲ	4 0%, 0%	9 67%, 67%	17 82%, 76%	34 88%, 88%

[1] Symbol “[” denotes included age, and symbol “)” denotes excluded age.

This is better illustrated as a histogram in Figure 1 where two-member and adult-like productions are shown per cluster per age group in succession. The distributions of two-member cluster productions per cluster across age groups as well as per age group across all clusters may be considered statistically normal as attested by the Kolmogorov–Smirnov test results, as follows. Per cluster across age groups: [ft]: $D = 0.265$, $p = 0.869$; [xt]: $D = 0.325$, $p = 0.692$; [fθ]: $D = 0.272$, $p = 0.853$; [fç]: $D = 0.296$, $p = 0.783$; [ðʝ]: $D = 0.159$, $p = 1.0$; [ɣð]: $D = 0.261$, $p = 0.881$; [mɲ]: $D = 0.324$, $p = 0.69$. Per age group across all clusters: [2;0–2;6): $D = 0.24$, 0.817; [2;6–3;0): $D = 0.183$, $p = 0.941$; [3;0–3;6): $D = 0.241$, $p = 658$; [3;6–4;0): $D = 0.274$, $p = 0.587$. It is seen that two-member productions differ more from adult-like productions in the oldest age group due to children having not acquired all consonants (see acquisition data of the children’s singeltons in Geronikou and Babatsouli (2024)), while being able to produce two-members, [xt]: (83%, 66%); [xθ]: (80%, 49%). A difference between the two measures for the oldest age group also appears for [ɣð]: (52%, 30%), although half of the children have not mastered two-member cluster production even by simplification with substitutions or any other phonological process. These productions with example words will be presented in detail in the Section 4 below. Furthermore, [ɣð], [fθ], and [ðʝ] are the most difficult clusters to acquire as half of the children are not able to produce them as a two-member cluster, whether adult-like or substituted, even by age 4;0.

The measures of two-member productions and adult-like productions can be considered as having no statistically significant difference as attested by the chi-squared results per cluster across age groups, as well as per age group across clusters. Per cluster across age groups: [ft]: $\chi^2 = 0.216$, $p = 0.642$, d.f. = 2; [xt]: $\chi^2 = 0.04$, $p = 0.850$, d.f. = 2; [fç]: $\chi^2 = 0.024$, $p = 0.887$, d.f. = 2; [ðʝ]: $\chi^2 = 0.01$, $p = 0.920$, d.f. = 2; [xθ]: $\chi^2 = 0.728$, $p = 0.394$, d.f. = 1; [ɣð]: $\chi^2 = 1.698$, $p = 0.194$, d.f. = 1; [mɲ]: $\chi^2 = 0.028$, $p = 0.867$, d.f. = 2. This shows that the two measures have lesser similarity for [ɣð] than the other clusters. Per age group across clusters with sufficient samples: [2;6–3;0): $\chi^2 = 0.051$, $p = 0.821$, d.f. = 4; [3;0–3;6): $\chi^2 = 0.434$, $p = 0.510$, d.f. = 6; [3;6–4;0): $\chi^2 = 3.057$, $p = 0.080$, d.f. = 7. This shows that the two measures have less similarity in the oldest age group than the other age groups.

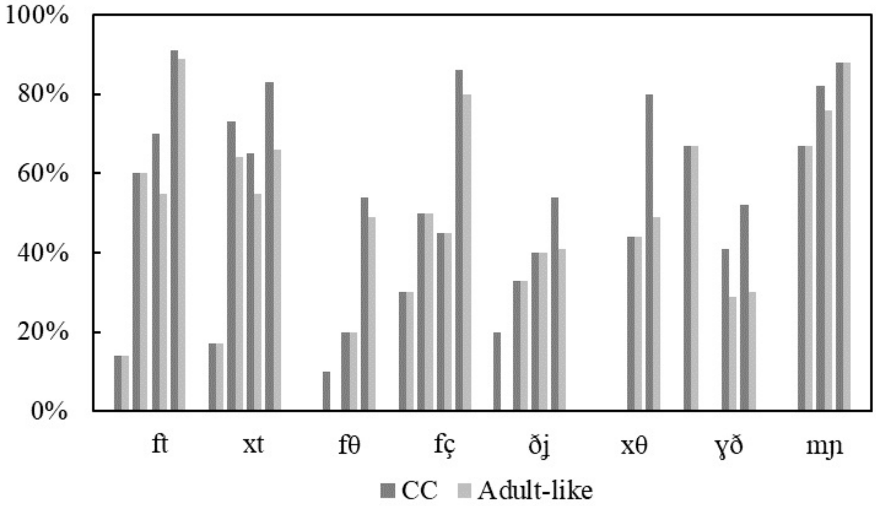

Figure 1. Two-member cluster productions by age group in ascending age order. Each of the four double bars represents an age group; the first double bar for each cluster represents the youngest age group, while the fourth double bar represents the oldest age group. The black color in the double bar denotes two-member productions (adult-like or not), and the gray color denotes adult-like two-member productions.

3.2. Cluster Reduction Patterns

Cluster reduction patterns, specifically cluster omission, reduction to the first member or its substitution, reduction to the second member or its substitution, reduction to one member either by coalescence or other phonological processes, are shown quantitatively in proportion to targets in Tables 3–6 for the four age groups under study. The sum of the reduction patterns is also presented. The last column of Tables 3–6 quantifies the mixedupness of the three main cluster stages: omission, reduction to one member, and two-member productions (e.g., Babatsouli & Sotiropoulos, 2018). The measure of entropy (Babatsouli et al., 2016) is selected to do this, which is defined as $-p_1\log(p_1) - p_2\log(p_2) - p_3\log(p_3)$, in which p_i is the proportion of each cluster stage to the targets, that is, $p_1 + p_2 + p_3 = 1$. The entropy normalized by the maximum entropy, which occurs when $p_1 = p_2 = p_3 = 1/3$, is independent of the choice of the logarithmic base, that is why this normalized entropy is computed and shown in the last column of Tables 3–6.

Table 3. Cluster reduction pattern at age [2;0–2;6).

	Reduction					
Cluster	**Ø**	**C1**	**C2**	**C**	**Sum**	**Cluster Stage Entropy**
ft	0.29	0.00	0.43	0.14	0.86	0.87
xt	0.00	0.00	0.67	0.16	0.83	0.42
fθ	0.60	0.20	0.20	0.00	1.00	0.61
fç	0.30	0.10	0.00	0.30	0.70	0.99
ðj	0.40	0.20	0.20	0.00	0.80	0.96
xθ	n/a	n/a	n/a	n/a	n/a	n/a
ɣð	0.33	0.00	0.00	0.00	0.33	0.58
mɲ	0.00	0.50	0.25	0.25	1.00	0.00

Table 4. Cluster reduction pattern at age [2;6–3;0).

Reduction						
Cluster	**Ø**	**C1**	**C2**	**C**	**Sum**	**Cluster Stage Entropy**
ft	0.00	0.20	0.20	0.00	0.40	0.61
xt	0.09	0.00	0.18	0.00	0.27	0.69
fθ	0.00	0.10	0.80	0.00	0.90	0.30
fç	0.00	0.21	0.21	0.07	0.49	0.63
ðʝ	0.00	0.11	0.45	0.11	0.67	0.58
xθ	n/a	n/a	n/a	n/a	n/a	n/a
ɣð	0.00	0.13	0.87	0.00	1.00	0.00
mɲ	0.22	0.11	0.00	0.00	0.33	0.77

Table 5. Cluster reduction pattern at age [3;0–3;6).

Reduction						
Cluster	**Ø**	**C1**	**C2**	**C**	**Sum**	**Cluster Stage Entropy**
ft	0.10	0.00	0.15	0.05	0.30	0.73
xt	0.00	0.00	0.25	0.10	0.35	0.59
fθ	0.10	0.20	0.50	0.00	0.80	0.73
fç	0.00	0.25	0.10	0.20	0.55	0.63
ðʝ	0.20	0.25	0.10	0.05	0.60	0.96
xθ	0.00	0.06	0.50	0.00	0.56	0.62
ɣð	0.00	0.18	0.29	0.12	0.59	0.62
mɲ	0.00	0.12	0.00	0.06	0.18	0.43

Table 6. Cluster reduction patterns at age [3;6–4;0).

Reduction						
Cluster	**Ø**	**C1**	**C2**	**C**	**Sum**	**Cluster Stage Entropy**
ft	0.00	0.00	0.09	0.00	0.09	0.28
xt	0.00	0.03	0.11	0.03	0.17	0.42
fθ	0.03	0.03	0.34	0.06	0.46	0.73
fç	0.00	0.11	0.00	0.03	0.14	0.37
ðʝ	0.03	0.09	0.17	0.17	0.46	0.73
xθ	0.00	0.00	0.20	0.00	0.20	0.46
ɣð	0.03	0.06	0.24	0.15	0.48	0.73
mɲ	0.00	0.06	0.06	0.00	0.12	0.33

Based on the results of Tables 3–6, the histogram of Figure 2 depicts the percentage of cluster reduction (omission plus reduction to one member) to cluster targets for each cluster per age group. As expected, there is an overall decrease in reduction with age. Only [mɲ] is reduced less than 20% by age 3;6, and only [fθ], [ðʝ], and [ɣð] are reduced more than 20%, at about 50%, by age 4;0. The ANOVA test results in F = 1.075, p = 0.408, d.f. = 2, which implies that there is no statistically significant difference in the variation in reduction between clusters with the variation in reduction within clusters.

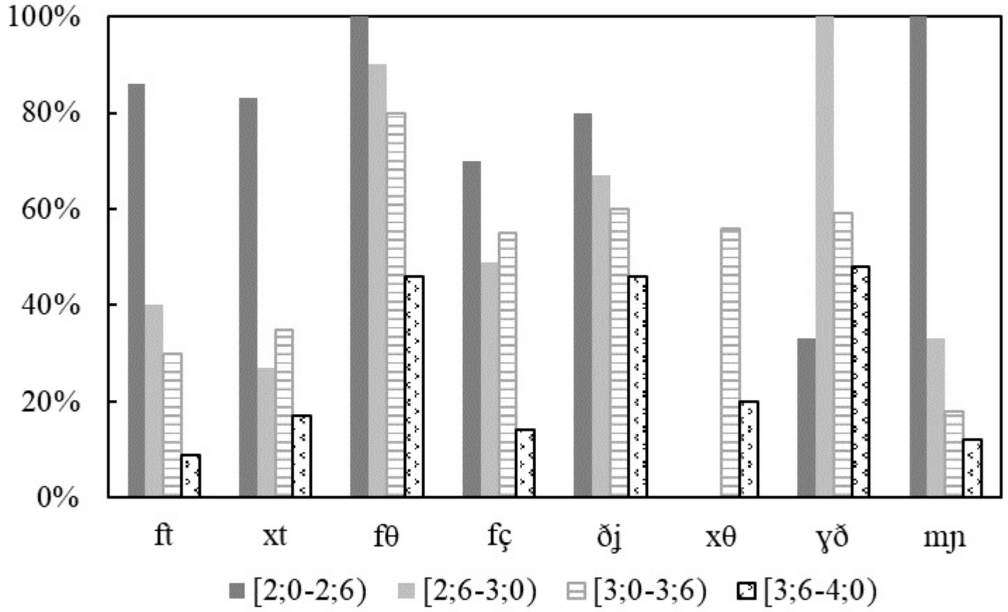

Figure 2. Cluster reductions (to one-member or omission) by age group in ascending age order. Each of the four bars represents an age group; the first bar for each cluster represents the youngest age group, while the fourth bar represents the oldest age group.

3.3. Cluster Reduction to a Single Member

The preference of cluster reduction to the first or second member has been discussed in the literature (see Section 1). However, there are no previously reported normative reduction data for Greek. Based on the results of Tables 3–6, the histogram of Figure 3 shows the relative reduction to the first or second cluster member by age group. For example, [ft] prefers reduction to the second member at all age groups except at ages [2;6–3;0) when reduction to each member is equal, 0.20 in proportion to targets, 50% of the sum of the reductions to each of the two members. The relative reduction to a member changes with age, although the preference to the member does not change with age, except for [ðɟ], for which no clear preference is shown. Among the remaining clusters, only [fç] and [mɲ] prefer reduction to the first member; all others prefer reduction to the second member.

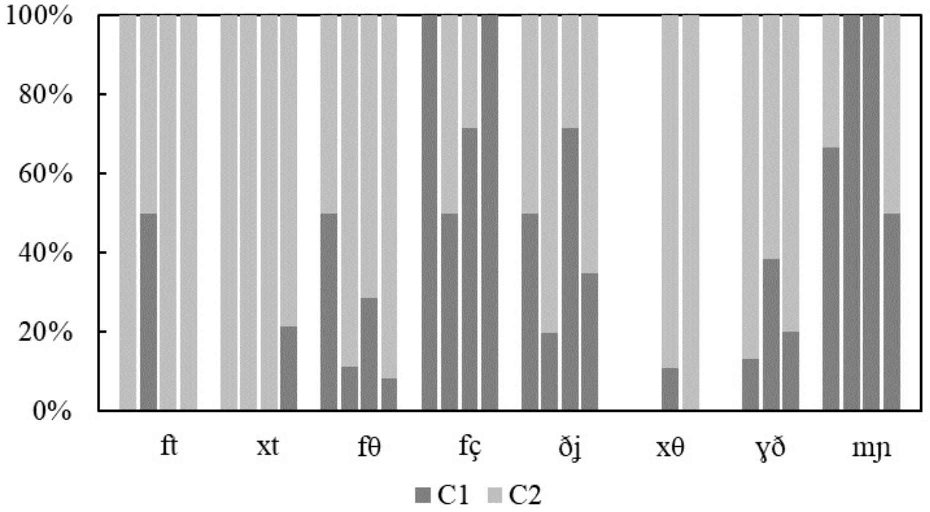

Figure 3. Relative cluster reductions to the first or second cluster member by age group in ascending age order. Each of the four bars represents an age group; the first bar for each cluster represents the youngest age group, while the fourth bar represents the oldest age group. Within each bar, the black color denotes reduction to C1 and the gray color denotes reduction to C2.

3.4. Entropy of Cluster Stages

The normalized entropy of three cluster stages (omission, reduction to one member, two-member production), as obtained in Tables 3–6, is shown in Figure 4 per cluster by age. Overall, there is considerable stage mixedupness across clusters and age groups. Even if there are only two stages present, 6% or larger in one stage results in 20% or larger entropy. This is why even [ft], which is produced with two members at the 91% level by age 4;0, has an entropy of 28%, resulting from 0% omission and 9% reduction to one member. Entropy values are exemplified by [fç] across ages. [fç] has an entropy of 99%, near 100%, in the youngest age group since all three stages are present with nearly equal weights (omission 30%, reduction to one member 40%, two-member production 30%). In the next two older age groups, it has an entropy of 63% because there is no omission, while the other two stages have nearly equal weights of 50%. The ANOVA test results in F = 1.207, *p* = 0.341, d.f. = 27 imply that there is no statistically significant difference in the variation in entropy between clusters with the variation in entropy within clusters.

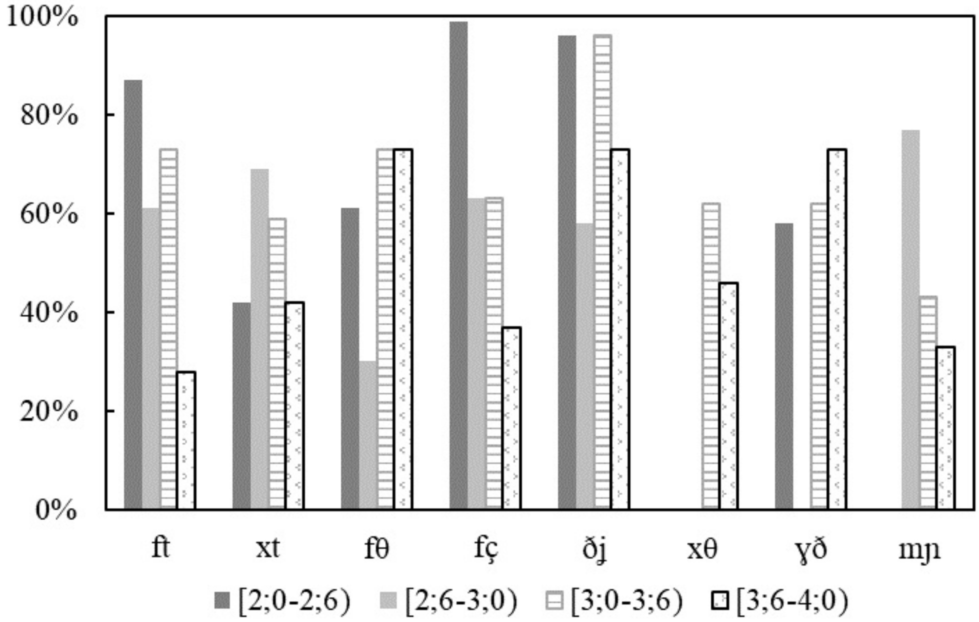

Figure 4. Entropy of cluster production stages by age group in ascending order. Each of the four bars represents an age group; the first bar for each cluster represents the youngest age group, while the fourth bar represents the oldest age group.

Table 7 gives the arithmetic average of cluster reduction patterns over all age groups and the resulting entropy of stage overlapping. [xt] and [xθ] have negligible cluster omission with nearly 40% reduction to one member and 60% two-member production resulting in an entropy near 63%. [fθ] and [ðʝ] have larger cluster omission than the rest at 18% and 16%, respectively, with reduction to one member at 61% and 47%, respectively, yielding larger entropies than the rest of 85% and 92%, respectively.

3.5. Cluster Reduction Including Omissions Across All Ages

Table 7 shows reduction patterns, including cluster omission (i.e., omission, reduction to the first member C1 or its substitution, reduction to the second member C2 or its substitution, reduction to a single member C by another phonological process) relative to all reductions.

These data are schematically depicted in Figure 5. In descending order, C2 dominates the reduction in [xθ] (92%), [xt] (74%), fθ, ɣð (58%), ft (54%), and [ðʝ] (37%), although for this cluster, omission and reduction to C1 are not much lower (25%). C1 dominates the reduction in [mɲ] (78%) and [fç] (35%), although for this cluster, reduction to C is not much lower (31%). Reduction to C is lower than 20% for all other clusters. Omission is higher than 20% and lower than 25% only for [ft], [fθ], and [ðʝ]. The ANOVA test results in F = 0, *p* = 1.0, d.f. = 27 imply that there is no statistically significant difference in the variation in reduction pattern between clusters with the variation in reduction pattern within clusters.

Table 7. Cluster reduction patterns across all ages.

Cluster	Reduction					
	Ø	**C1**	**C2**	**C**	**Sum**	**Cluster Stage Entropy**
ft	0.10	0.04	0.22	0.05	0.41	0.82
xt	0.02	0.01	0.28	0.07	0.38	0.68
fθ	0.18	0.13	0.46	0.02	0.79	0.85
fç	0.08	0.17	0.08	0.15	0.48	0.83
ðʝ	0.16	0.16	0.23	0.08	0.63	0.92
xθ	0.00	0.03	0.35	0.00	0.38	0.60
ɣð	0.09	0.09	0.35	0.07	0.60	0.84
mɲ	0.06	0.20	0.08	0.08	0.42	0.78

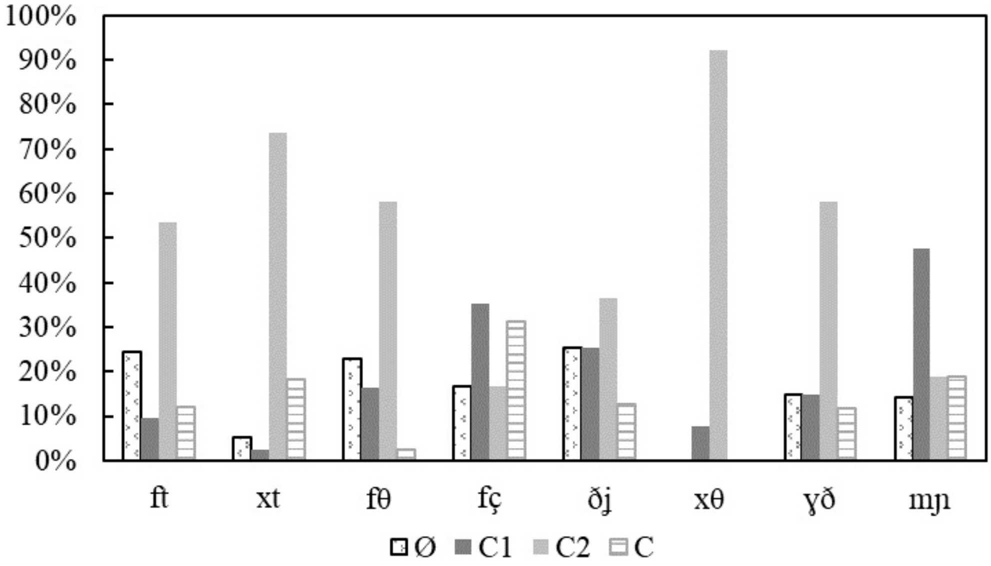

Figure 5. Relative cluster reduction patterns across all age groups. Each of the four bars represents a reduction pattern. The first bar (dotted) for each cluster represents cluster omission, the second bar (black) represents reduction to C1, the third bar (gray) represents reduction to C2, and the fourth bar represents reduction to a single C, that is not the first or second member, nor their substitutions.

Last, the most prevalent patterns of relative cluster reduction given quantitatively in Figure 5, are summarized qualitatively in Table 8 and further discussed comprehensively in the last part of the Section 4.

Table 8. Cluster reduction patterns.

Cluster	Reduction to
ft, xt, fθ, xθ, ɣð	C2
mɲ	C1
ðʝ	C2, C1, Ø
fç	C1, C

4. Discussion

This section elaborates on the results addressing our research questions regarding cluster accuracy, cluster stage overlapping, and cluster production patterns. Before we embark on that, however, a brief comment is pertinent. Phonological acquisition, of which cluster development is a dynamic process and rooted in sociobiological (ecosystemic) approaches to deciphering language acquisition (e.g., Babatsouli, 2024). An "adequate approach" to explaining specific linguistic behaviors requires that we "look at the psycholinguistic validity in a theory" (Ball, 2003, p. 28); this entails considering system-internal and system-external parameters. Such adequacy may be obtained by pulling together major theoretical approaches as exemplified by universal (Greenberg, 1963; Pye et al., 1987), generative (e.g., distinctive features), natural (e.g., phonological processes), non-linear (multi-tiered representations), input/usage-based frameworks, psycholinguistic models (cognitive processes), etc. (e.g., Archibald, 2010; Bernhardt & Stemberger, 1998; Bybee, 2010; Chomsky & Halle, 1968; Ingram, 1989; Stampe, 1973; Prince & Smolensky, 2004). The influential sociolinguist, Labov (2004) defines a "linguistic variable", as determined by the "principle of accountability" and "the axioms of probability theory", as that which requires statistical analyses to decipher the distribution of data and the interdependence of overlapping variables (Babatsouli, 2024). In what follows, analyses combine such quantitative and theoretical frameworks, ultimately aiming to guide clinical practice where such frameworks find clinical application (Ball & Kent, 1997; Bernthal et al., 2013; Ingram, 1998). We are proponents of closing the gap between abstract linguistic theory and real-life applications, making our findings more easily accessible to practitioners who struggle with time constraints (e.g., Babatsouli, 2023) while remaining grounded and rounded.

4.1. Accuracy Levels of Two-Member Clusters

Recent cross-sectional data on Greek cluster acquisition by Geronikou and Babatsouli (2024) report earlier acquisition of falling sonority two-member clusters (CC) compared to level sonority CC clusters. We have also concluded that our experimental result is further backed up by the cross-sectional evidence we identified in the report of the Panhellenic Association of Logopaedics [PAL] (1995) and Papathanasiou et al. (2012). Our inference is supported by cluster frequency data in Greek (Protopapas et al., 2012), as shown only for [ft] (4.5%), [ðj] (1.8%), and [fθ] (1.0%), since the study does not report frequency data for the remaining clusters we are investigating here. This observed relationship between input (distributional frequencies) and order of acquisition taps on language universals (Greenberg, 1963), in that the most frequent linguistic unit in language input has a higher functional load specific to the phonotactics of the language (Pye et al., 1987), is less marked, and thus earlier acquired.

4.1.1. Falling Sonority Clusters [ft, xt]

Our data show that among the clusters with decreasing sonority, [xt] with $\mathrm{C1}_{\mathrm{Dorsal}}$ in *χτένα* [ˈxtɛ.nɐ] "comb" is acquired by 75% of children aged 3;0–3;6, earlier than [ft] with $\mathrm{C1}_{\mathrm{Labial}}$ in *φτερά* [ftɛ.ˈɾa] "feathers", acquired between ages 3;6–4;0. While both clusters are in the psycholinguistically prominent word-initial position, [ft] is elicited in a weak (unstressed) prosodic context, in that the syllable is not stressed, which is known to develop more slowly (e.g., Ingram, 1989). Other early cross-sectional studies do not show different acquisition levels for [ft, xt], though these clusters are shown to be acquired six months later (4;0–4;6) for [ft] (Papadopoulou, 2000) and [ft, xt] (Papathanasiou et al., 2012). The norms in the Panhellenic Association of Logopaedics [PAL] (1995) indicate that stressed [xt] is also acquired at 4;0–4;6 in multisyllabic *χτύπησε* [ˈxti.pi.sɛ] "hit", earlier than unstressed word-medial [ft] at 4;6–5;0 in *ναύτης* [ˈnɐftis] "sailor"; this further supports our findings. The

Panhellenic Association of Logopaedics [PAL] (2005) reported [ft, xt] in children's phonetic inventories by ages 3;7–4;0. Not all data are directly comparable, however, in that cluster production is sometimes elicited in variable prosodic/lexical contexts, but this further validates the significance of deciphering non-linear levels of phonological representation as well as lexical influences on phonological acquisition (Bernhardt & Stemberger, 1998; Ferguson & Farewell, 1975).

4.1.2. Level Sonority Clusters

Level sonority complex onsets, C1C2, in this study can be grouped into (i) five types comprising pairs of obstruents, three of which are voiceless sequences [fθ, xθ, fç], and two pairs are voiced [ɣð, ðʝ]; and (ii) a single cluster comprising a pair of nasals: [mɲ]. Among the obstruent clusters, [fç] and [ðʝ] involve allophones /x/→[ç], /ɣ/→[ʝ]_i, i+V as C2, (resulting from /CiV/→[CV], c.f. Babatsouli, 2019; Okalidou & Babatsouli, in press). The age of acquisition of these clusters is reported next.

Voiceless Obstruent CCs [fθ, xθ, fç]. Geronikou and Babatsouli (2024) report acquisition in 75% of the children between ages 3;0 and 6;6. The study showed the following: [fç] in *φίογκος* [ˈfço.gos] "a bow" is the earliest acquired by ages 3;0–3;6, [fθ] in *φθινόπωρο* [fθi.ˈno.po.ɾo] "autumn" comes next by 5;6–6;0, followed by [xθ] in *χθες* [xθɛs] "yesterday" by 6;0–6;6. There are no previous reports of developmental norms for these clusters except for Geronikou and Babatsouli (2024). The evidence in the Panhellenic Association of Logopaedics [PAL] (1995) shows early acquisition of Greek palatal fricatives between Stages I and II (ages 2;6–3;6) (for early acquired [ɲ] at 2;7 in bilingual L1 Greek see Babatsouli, 2020a). Such findings paired with unmarked (easier to acquire) $\mathrm{C1}_{\mathrm{Labial}}$ (e.g., de Lacy, 2006; Jakobson, 1941/1968) explain early mastery of word-initial [fç] in a stressed context. Effects of weak syllables, word length (Ingram, 1989), and place markedness can be seen, however, in the delay of [fθ] despite C2COR also being unmarked (Prince & Smolensky, 2004; Malikouti-Drachman, 2001 for Greek).

Voiced Obstruent CCs [ɣð, ðʝ]. The acquisition level of cluster [ɣð] is first reported by Geronikou and Babatsouli (2024). Cluster [ðʝ] shows disparate ages of acquisition across existing reports. A 6-month difference on the same elicited word *διαβάζει* [ðʝɐ.ˈvɐ.zi] "reads" is acquired at 3;6–4;0 in Geronikou and Babatsouli (2024), six months later by 4;0–4;6 in the Panhellenic Association of Logopaedics [PAL] (1995), but after age 6;0 in Papathanasiou et al. (2012). Our study shows unstressed [ðʝ] in multisyllabic *διαβάζει* [ðʝɐ.ˈvɐ.zi] "reads" much earlier acquired (3;6–4;0) than stressed [ɣð] in *γδέρνει* [ˈɣðɛɾ.ni] "scratches" (6;0–6;6). While place markedness hierarchies in terms of Coronal, Dorsal (see refs above), and prosodic prominence/weakness per se do not help explain the disparate results for [ɣð, ðʝ], it can be argued that the Place Feature Reversal of $\mathrm{C1}_{\mathrm{DOR}}\mathrm{C2}_{\mathrm{COR}}$ in [ɣð] requires more advanced motor skills to facilitate the articulatory sequence Back-to-Front than that required by the articulatory sequence Front-to-Back of $\mathrm{C1}_{\mathrm{COR}}\mathrm{C2}_{\mathrm{DOR}}$ in [ðʝ], which abides by Coronal less marked than Dorsal in acquisition (Jakobson, 1941/1968). This marked Place reversal pattern also explains the earlier acquisition of [fθ] compared to [xθ], which was discussed in the previous paragraph. Word frequency and word complexity are additional determinants. The Greek word *διαβάζει* [ðʝɐ.ˈvɐ.zi] is more common in Greek than *γδέρνει* [ˈɣðɛɾ.ni] (e.g., Kyparissiadis et al., 2017), especially in child speech. Also, the occurrence of heterosyllabic cluster in [ˈɣðɛɾ.ni], which also comprises the rhotic (a late acquired sound in Greek), may have additionally contributed to slower development since simultaneously targeting non-acquired consonants and/or clusters makes the word more complex and, thus, more difficult. It is known that consonant clusters mark a significant departure in phonotactics from the earlier unmarked syllables (e.g., CV, VC) (Ingram, 1989), which requires increasing maturation of the motor speech mechanism and development of anatomical oromusculature (e.g., McLeod et al., 2001a, 2001b).

Nasal CC [mɲ]

Word-initial cluster [mɲ], which involves a Nasal + Nasal sequence, is also underrepresented in the acquisition literature cross-linguistically. Our study shows stressed [mɲ] acquisition in *μοιάζουν* [ˈmɲɐzun] "they look alike" by ages 3;6–4;0. This matches the acquisition data for Greek medial onset [mn] (Geronikou & Babatsouli, 2024) in *λίμνη* [li.mni], the PAel word used to elicit productions of this cluster (Babatsouli, 2019). While no previous study reports acquisition norms for [mɲ], the Panhellenic Association of Logopaedics [PAL] (1995) showed that word-medial tautosyllabic [mn] is acquired in *λίμνη* [ˈli.mni], six months later at ages 4;0–4;6. These results indicate a marked delay for this cluster type, compared to the finding that a single child acquired the contrast by 2;7 (Babatsouli, 2020a). This is evidence of either methodological disparities across studies or individual variation in child speech (e.g., Ingram, 1989; Locke, 1989).

An Inference Regarding Greek Palatal Allophones as C2

All $C1_{FRIC}C2_{FRIC}$ clusters discussed in the study that comprise a Greek palatal allophone in complementary distribution (e.g., Babatsouli, 2019) as C2 are acquired earlier than clusters that contrast the representation of member constituents underlyingly, /C1C2/→[C1C2]. It is noted that the development of such clusters has not been documented before with cross-sectional data for Greek (or for any other language, to our knowledge). As shown in the introduction, Greek clusters, /C1iV/→[$C1C2_{PAL}$V], involve Greek palatal obstruents [ç] and [ɟ] and the palatal nasal [ɲ]. Setatos (1974) includes /i/ in the representation of Greek syllables underlyingly (e.g., CiV, CVi, CCiV, etc.), with /i/ being a vocalic onglide or offglide in a branching nucleus, which commonly surfaces as a semi-vowel [j] because the two segments are phonetically very close (e.g., Bernhardt & Stemberger, 1998). Based on Setatos' (1974) representation of syllables (/CiV/, /CVi/, /CCiV/, etc.), we assume an underlying vowel in /CiV/, but this does not contradict other reports of a semi-vowel /j/ in this context, that is, /CjV/, whereby the phonological process at hand is described as fortition of /j/ to [ç], [ɟ], or [ɲ], (Revithiadou, 2021), i.e., /fjo/→[fço], /ðja/→[ðɟɐ], and /mja/→[mɲɐ]. The segmental strengthening witnessed can also be characterized as a palatalization process when fortition is specified further. Topintzi and Baltazani (2016) have documented the dual nature of glide /j/ as both a distinct phoneme and an allophone of /i/. They also document that glide strengthening and palatalization are equivalent processes. There is an underlying prosodic contrast between the single branching onset /CiV/, though not as optimal as /CV/ (Clements, 1990b), and the branching onset /CCV/. Consequently, these produced clusters, [$C1C2_{PAL}$V], have a single onset underlyingly, while also being phonemically represented by a rise in sonority from single onset to the branching nucleus, itself forming a rising sonority peak, as dictated by the vowel sonority scale (e.g., de Lacy, 2004, and refs therein), adjusted here for Greek in Figure 6.

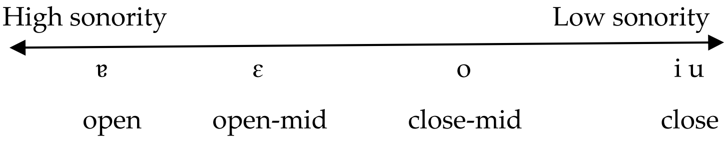

Figure 6. Greek vowel sonority scale.

Diphthong /iV/, therefore, abides by the universal phonotactic rules on syllable well formedness: segment constituents increase in sonority from left to right on the left edge of the word. Our data provide evidence of sonority being a guiding force in children's mental representation of the prosodic context of these clusters in their targeted language, Greek. The sonority effect, we have described, is arguably veiled in that it functions in the underlying representation of the respective targeted syllable at the phonemic level (which is represented by a rise in sonority) but is not immediately apparent in the surface representation of the targeted cluster at the phonetic level (which is represented by level sonority). The veiled sonority effect we have identified for these targeted clusters in Greek elucidates the children's developmental cluster patterns in the study.

As part of the branching nucleus (Selkirk, 1984), the diphthong's onglide, weak vowel /i/, can behave variably when realized in Greek because of its subsidiary status to strong vowels (e.g., Kenstowicz, 1997). Its predominant realization is a palatal consonant (see Recasens, 2020 for comprehensive coverage), /CiV/→[C1C2V], i.e., [CC_{PAL}V], which does not alter the status of the stronger offglide [ɐ, ɛ, o] that still dominates the nucleus. Subject to stylistic speaker- or context-specific tendencies, onglide /i/ may alternatively surface, vocalically taking over the syllable nucleus itself, [CV_i]. In this later scenario, there is no choice for the original stronger vowel but to be syllabified separately (e.g., Kenstowicz, 1997). The word *διαγώνισμα* "test" is a good example of such varisyllabic word production patterns: /**ðiɐ**.ˈɣo.ni.smɐ]→[**ðɟɐ**.ˈɣo.ni.zmɐ]∼ [**ði.ɐ**.ˈɣo.ni.zmɐ]. However, not all words/syllables comprising Greek palatal allophones are consistent in showing such free variation; this phenomenon occurs in words of learned origin (Warburton, 1976, p. 275).

We conclude, by inference, that because Greek /CiV/→[CC_{PAL}V] clusters are underlyingly less marked due to their single onset and vocalic rise in sonority, they contrast with level sonority clusters represented so underlyingly (not phonetically), such as /fç/→[fç], /ðɟ/→[ðɟ], and /mɲ/→[mɲ], likely permitted by other languages' phonotactics (e.g., Ingram & Babatsouli, 2024). In our study, this is the case for remaining Greek level sonority clusters, like [ɣð], whose members, [ɣ] and [ð], are phonemically represented fricatives, /ɣ/, /ð/, of equal (thus level) sonority. Greek-speaking children acquire clusters with palatal fricatives earlier than the clusters that involve a Fricative + Fricative cluster underlyingly. This is further indication that Greek palatal allophones are early acquired and less marked compared to most non-palatal segments. Such evidence of a preference for unmarked productions in Greek clusters (though not the only one) supports the known dictum that onset clusters of rising sonority are universally less marked, as overwhelmingly reported for Obstruent + Sonorant consonant clusters in cross-linguistic research (see discussions in Babatsouli, 2016b, 2018; Barlow, 2016; Klopfenstein & Ball, 2010; D. Ohala, 1999; Kirk & Demuth, 2003; Parker, 2012; Pater & Barlow, 2003, etc.).

Our inference is further supported by previous claims for an implicational universal that contrasts phonemic and surface representations in cluster development (O'Connor, 2001). We further go ahead to argue that although Greek Obstruent + Obstruent clusters violate "the minimal sonority distance of $\geq$4 … [thus] being referred as "antisonority" clusters" (Kappa, 2002, p. 9), this does not hold for Greek clusters comprising a palatal allophone. The fact that /piVC/→[pç] is acquired at the same time as /pl/→[pl] (3;6–4;00), but earlier than /ps/→[ps] (4;0–4;6) in Greek, an inference we make based on data from the Panhellenic Association of Logopaedics [PAL] (1995), is empirical evidence of our proposition with data outside this study.

The earlier acquisition of Nasal + Nasal compared to Obstruent + Obstruent is documented by our merged quantitative results on [mɲ] and [mn] acquisition, here, showing 76% acquisition by age 3;0–3;6. We see that [mɲ] and [mn] do not seem to be differentiated in the available data here (and in Geronikou & Babatsouli, 2024). These findings support Jakobson's (1941/1968) markedness hierarchy, whereby Labial is the least marked place of articulation. Greek [n] is acquired early (by 2;0–2;6, Geronikou & Babatsouli, 2024), as is Greek [ɲ] (by age 2;6, Thomadaki & Magoula, 1998). Babatsouli (2020a) also reports [mɲ] acquired in bilingual L1 Greek by 2;7, earlier than the child's other clusters. Cross-linguistic research shows that /m, n/ are 75%-85% acquired by 1;10–2;10, while phoneme /ɲ/ (not the palatal allophone in Greek) is acquired by 3;0–3;11 (McLeod & Crowe, 2018). Such evidence indicates that Labial and Coronal nasals are unmarked and early acquired, but the phonemic palatal nasal is slower to acquire. It can be seen, thus, why Greek /mn/ and [mɲ] (with its veiled rise in sonority) are unmarked compared to Obstruent + Obstruent.

A Reminder Regarding the Quantitative Results

It is worth reminding that the most marked, and thus last acquired, cluster [ɣð], in this study is produced well, as percentages indicate, by the youngest group of children (ages 2;0–2;6) compared to older groups. This is because there are fewer elicitations of the words (mostly verbs) in which the clusters were targeted. Younger children have more difficulty in word retrieval of abstract words, like verbs and adverbs, in word naming elicitation tasks. Similarly, /xθ/ is not attempted by children in the first two age groups. All other clusters improve with children's increasing age (Table 2).

4.1.3. Cluster Production Patterns in Relation to Adult-like Productions

This section summarizes the quantitative results of two-member cluster productions in relation to adult-like productions. Two-member cluster productions result from simplification (phonological) processes (Stampe, 1973) leading to substitutions of C1 and/or C2, as one of the known overlapping stages of cluster acquisition (see Babatsouli & Sotiropoulos, 2018 for measuring developmental cluster stages, first reported qualitatively by Greenlee (1974)). Demuth and McCullough (2009) argue that two-member productions of targeted two-member clusters are considered acquired, as indicated by their faithfulness to the targeted prosodic structure. Our data (Table 2, Figure 1) support this argument since there is no statistically significant difference per cluster across age groups or per age group across clusters. Exceptions are clusters [xt]: (83%, 66%); [xθ]: (80%, 49%); and [ɣð]: (52%, 30%), which show the largest divergence between accurate (adult-like) and developmental two-member clusters (simplified, non-adult-like) in the older group of children in Table 2. These are also more marked in terms of accuracy levels, as already shown. This is because the children still struggle with clusters, as indicated by the simplification patterns in their productions. Two-member productions and the operant phonological processes are summarized in Table 9.

Table 9. Non-adult-like cluster productions [CC].

		Substitutions				
Cluster	**C1$_{\text{SUB}}$**	**C2$_{\text{SUB}}$**	**C1$_{\text{SUB}}$/C2$_{\text{SUB}}$**	**Metathesis C1$_{\text{SUB}}$/C2$_{\text{SUB}}$**	**Epenthesis**	**Added σ Complexity**
ft	pt, st	fθ	-	ts	ɐpt	
xt	kt, st, θt	-	-			
fθ	-	fl	-	sf		
fç						
ðʝ	vʝ		-			
xθ	kθ		kt	ts, ft, xt, xl,	ɛxθ, ɛkt, ɛxt	xθt
ɣð		ɣl, ɣɾ		ðɾ		
mɲ		ml				

The following remarks are pertinent:

(i) More substitutions target one member, C, in the cluster than both members, CC, which supports the principle of articulatory economy (Clements, 2003).

(ii) C1 is targeted more times for substitution than C2 is, being psycholinguistically more prominent, though resulting substitutions are unmarked in manner (Plosives) or place (Labial).

(iii) The overwhelming number of substitutions that do not agree in place with target are faithful to Coronal, known to be the universally unmarked place/frequent (Bernhardt & Stemberger, 1998; Maddieson, 1984); [ðʝ] is markedly an exception being substituted by labial [vʝ] because the target /ð/ is Coronal.

(iv) Substitutions are more faithful to place than manner in the targeted member; note the regressive place/manner assimilations in /ftɛɾɐ/→[ptɛlɐ], [fθɛlɐ].

(v) Simplification of level sonority sequences involving C2 substitution results mostly in rising sonority sequences, so [ɣð]→[ɣl], [ɣɾ], [fç]→[fl]. This indicates that the children have learned the rule for syllable well formedness (a sonority rise from onset to the nucleus). Phonetically, the sonorants are facilitated by regressive assimilation to /ɾ/ or its substitution [l] in /ɣðɛɾni/ "scratches" and /fθinopoɾo/ "autumn".

(vi) Epenthesis is very infrequent; notably, the epenthesis in [ɛxθ, ɛkt, ɛxt] is more likely lexically driven, since *χθες* [xθɛs], *εχθές* /ɛxθɛs/ "yesterday" are stylistic lexical variants. Epenthesis of a vowel occurred prior to the cluster, with no vowel inserted between the consonants. This was considered a stylistic variation and did not affect the consonantal combination or cluster structure.

(vii) Metathesis takes up about 50% of the operant phonological processes, most of which result in a rise in sonority either involving obstruents or a sonorant as C2 sequence patterns. Exceptions are in late acquired /xθ/ produced with the unmarked (in terms of acquisition level) falling sonority sequences [ft, xt], and /fθ/ produced as an adjust cluster [sf]. This indicates that children have an accurate representation of syllable well formedness, though they have not yet mastered adult-like productions.

(viii) All productions obey Greek initial onset phonotactics, except in [ml] for [mɲ]. The [l], substitution for adult [ɲ] violates syllable formedness in terms of sonority, and it is explained as resulting from regressive assimilation to the coronals in [mɲɐzun] "they look alike", as the child practices production of clusters. It is known that employing complexity facilitates learning (Babatsouli, 2016a, and refs. therein for clinical contexts).

(ix) [xθt] is another example of complexity as a typical developmental mechanism, this time involving added syllable, σ, complexity by consonant epenthesis, originally documented as an infrequent developmental norm in bilingual English and Greek, as also indicated by the identification of cross-linguistic data (Babatsouli, 2016a).

4.2. Cluster Reduction Patterns

Cluster reduction patterns, defined here as cluster omission, and reduction to C1, C2, or their substitutions, or reduction to a single C by other phonological processes, such as coalescence, metathesis, and assimilation, are discussed next. Based on the reported percentages of cluster reduction to their respective targeted cluster per age, we can confirm the anticipated decrease in cluster reduction. Persisting reductions are evidenced for targeted [mɲ] still by age 3;6, and for targeted [fθ], [ðʝ], and [ɣð] still by age 4;0 (Tables 3–6). A child with phonological delay showed more reductions word-initially than word-medially in Fricative + Fricative clusters (Babatsouli & Geronikou, 2022). Watson and Scukanec (1997) found that cluster simplification (defined as two-member production with substitution) increases with age between 2;0 and 3;0, while cluster reduction (not including omissions) decreases during the same period. This is supported by our quantitative data analyses in the Section 3 (Tables 2–6). Babatsouli (2016b; see also report in Okalidou & Babatsouli, in press) as the following was reported for a child's speech from age 2;7 to 4;0: (i) reductions dominate until 2;8 in Obstruent + Obstruent, (ii) it takes about two months for cluster productions to go from reduction to single member production, and then to two-member production. These findings were independent of cluster type, sonority, and singleton mastery. Our quantitative data indicate the following markedness hierarchy in (2) for cluster reductions near acquisition (3;6–4;0), which align with the acquisition level findings reported earlier, in that falling sonority clusters are less marked than level sonority clusters. The qualitative data show more reduction to C in /xθ/ than in [fθ].

[ft] >> [mɲ] >> [fç], [ðɟ] >> [xθ] >> [fθ] >> [ɣð]
Less marked More marked

This last part of the section elaborates on the mixedupness (or overlapping) of developmental cluster stages using entropy (e.g., Babatsouli, 2020b, 2021; Babatsouli & Sotiropoulos, 2018; Babatsouli et al., 2016). Child developmental speech shows production variability that is characterized by mixedupness (or the overlapping of the different production patterns). This is because linguistic (and phonological) systems are dynamic and in flux, which is especially true in language acquisition (e.g., Babatsouli, 2024). Entropy is a scientific concept used to determine system evolution, and systems in nature "evolve from states of perfect "order" to states of total "disorder", so that "increasing mixed-up-ness is consistent with increasing entropy" (Seitz & Kirwan, 2022, p. 1090). Well-known quantitative phonological measures, e.g., the percentage of consonants correct (PCC), phonological mean length of utterance (pMLU), and phonological word proximity (PWP), depend linearly on their components and their sensitivity to component changes is constant rather than dynamic (Babatsouli et al., 2016). These measures lack the sensitivity to facilitate differentiation between variable speech production patterns such as adult-like, substituted, or deleted speech sound tokens in a child's speech sample. Such mixedupness of variable production patterns can be evidenced in the same child's different speech samples or in the same or different speech samples across different children. Entropy, unlike the linear measures, is used to measure mixedupness of both grammatical and phonological components, the latter initiated by Roman Jakobson (see Goldsmith, 2000).

Cluster production variability (e.g., reduction to one of the members, member substitutions, or cluster omission) is referred to as cluster stages, which were shown to overlap (co-occur) even with a single child's reiterations (Greenlee, 1974). Measuring the mixedupness of children's cluster productions involves the quantitative comparison of the proportions of cluster stages to targets (e.g., Babatsouli & Sotiropoulos, 2018). In mathematical terms, entropy, which is adapted from information theory (Goldsmith, 2000), is defined as being equal to $-p_1\log(p_1) - p_2\log(p_2) - p_3\log(p_3)$, in which p_i is the proportion of each cluster stage to the targets, so that $p_1 + p_2 + p_3 = 1$. Similar proportions of stages result in a larger entropy and dissimilar proportions of stages result in a lower entropy. Maximum entropy occurs for equal proportions of stages (omission, one-member productions, two-member productions), that is, $p_1 = p_2 = p_3 = 1/3$, and is equal to log3. Minimum entropy occurs when two of the three stages are absent from cluster productions ($p_1 = p_2 = 0$, $p_3 = 1$), in which case entropy becomes zero. When one of the stages is absent from cluster productions ($p_1 = 0$) and the other two stages have equal proportions to targets ($p_2 = p_3 = 1/2$), entropy becomes equal to $-\log(1/2) = \log 2$. For entropy that is independent of the choice of the logarithmic base, the score is normalized (divided) by its maximum value, log3. This is so because $\log_b a/\log_b 3 = \log_c a/\log_c 3$ given that $\log_b a = \log_c a/\log_c b$. This is the reason why the normalized entropy is computed and shown in the last column of Tables 3–6 for the production stages of each cluster in each age group. Entropy was computed here, focusing only on omissions, single member, and two-member productions. As expected, because speech variability is a developmental norm (Dinnsen, 1992), we are quantitatively documenting for considerable stage mixedupness across cluster types and child age groups. Our results also indicate that entropy variation is not statistically significant between clusters compared to the variation in entropy within clusters. There are no such studies in the literature to compare these findings with.

4.3. Cluster Reduction to a Single Member

This simplification pattern is common, and, thus, frequently investigated in cross-linguistic research, as shown in the Introduction. McLeod et al. (2001b, and ref therein) also report quantitative reduction norms for English. Nevertheless, there are no quantitative reports on cluster reduction previously reported for Greek. To summarize our results, Figure 3 documents the relative reduction to C1 or C2 by age group. As was noted for [ft], for instance, reduction to C2 is documented across ages except at 2;6–3;0. We found the relative reduction to a single member changed with age, but the cluster member preference remains constant with age across clusters. The only exception is [ðɟ], which shows variability in the reduction patterns. Among the remaining clusters, [fç] and [mɲ] mostly reduce to C1, while all other clusters mostly reduce to C2. These patterns are summarized in Table 8.

Next, we highlight single member productions in Table 10, and we discuss major observations focusing first on adult-like productions, followed by substitutions. Table 10 includes adult-like substitutions, as previously suggested in Table 8. When there is a substitution that changes the targeted manner of articulation, this is noted in bold.

Table 10. Single onset productions, [C] [1].

Productions									
	Adult-like			Substitutions					
Cluster		**C_{-CONT}**		**C_{+CONT}**		**$C_{\pm CONT}$**		**C_{SON}**	
ft	t	$C_2 \rightarrow$	d	$C_{OAL} \rightarrow$	s			$C_2 \rightarrow$	**l**
xt	t	$C_1 \rightarrow$	**c**					$C_2 \rightarrow$	**n, l**
fθ	θ	$C_1 \rightarrow$ $C_2 \rightarrow$	p **t**	$C_2 \rightarrow$ $C_{PAL} \rightarrow$	s ç			$C_2 \rightarrow$	**n, l**
fç	f	$C_2 \rightarrow$	**c**, ɡ	$C_1 \rightarrow$ $C_2 \rightarrow$ $C_{OR} \rightarrow$ $C_{LAB} \rightarrow$	v ɟ s f, v	$C_{OR} \rightarrow$	**dz**		
ðɟ	ð, ɟ	$C_1 \rightarrow$	**d**	$C_1 \rightarrow$ $C_2 \rightarrow$	z ɣ	$C_{OR} \rightarrow$	**dz**	$C_1 \rightarrow$	**n**
xθ	θ	$C_2 \rightarrow$	**t**	$C_2 \rightarrow$ $C_1 \rightarrow$ $C_{LAB} \rightarrow$	s ç v				
ɣð	ð			$C_2 \rightarrow$ $C_1 \rightarrow$	z ɟ			$C_2 \rightarrow$	**n, l**
mɲ	m	$C_2 \rightarrow$	**d**					$C_2 \rightarrow$	**n, l**

[1] C_1: Ć1; C_2: Ć2; C_{LAB}: labial; C_{OR}: coronal; C_{OAL}: coalescence; C_{SON}: sonorant; in bold: manner change.

4.3.1. Adult-like Single Member Productions

We see that Obstruent + Obstruent clusters predominantly reduce to C2 (mostly a Coronal, but also a Palatal) irrespective of the sonority pattern, but Nasal + Nasal reduces to C1 (Labial). Among the Obstruent clusters, initial ones with Palatal C2 are produced variably depending on the place of articulation of C1. When C1 is Labial, [fç], they reduce to C1, or they are substituted (see Table 8). When C1 is Coronal, [ðʝ], they show a lack of preference for either C1 or C2. The reduction to Labial is also evidenced in Nasal + Nasal, [mɲ], which reduces to [m]. This may be explained by the fact that labials, [m, f] are less marked than interdentals cross-linguistically (e.g., Maddieson, 1984, or Babatsouli, 2017, for a bilingual study). Greek labials, [m, f], are also acquired earlier than interdentals (see, e.g., Panhellenic Association of Logopaedics [PAL], 1995). Given the early acquisition of palatal singletons in Greek and the lack of evidence for preference to C2 in [ðʝ], the reduction is investigated further by looking at the prosodic structure.

The literature on cluster reduction patterns differentiates between featural prominence (sonority) and structural prominence (headedness); the member to which a cluster reduces is considered the head (Goad & Rose, 2000, and refs therein). Goad and Rose (2000) distinguish two reduction patterns for s-clusters (called "adjuncts" because /s-/ is considered an appendix to the syllable, rather than part of the onset, and differentiated from"true" branching onsets, e.g., Yavaş & Babatsouli, 2016, for bilingual L1 Greek). Goad and Rose (2000) refer to these as the "sonority pattern" and the "head pattern". The authors also argue that "children initially make decisions about headedness on the basis of sonority until the distributional facts are understood" (p. 1). As we saw, in the case of clusters with C1 Labial and C2 Palatal, [mɲ, fç], Labial is the unmarked head surviving. In [ft], the unmarked Coronal, and non-sonorant [t] unequivocally survives. In Obstruent clusters not involving C2 Plosive or Palatal, i.e., [fθ, xθ, ɣð], however, reduction prefers C2 Coronal place, the universally unmarked place of articulation, though interdentals are most marked among the Coronal sounds.

Actual qualitative variability in reduction is evidenced in [ðʝ], which involves the voiced interdental coronal as C1, and palatal as C2. In the case of other clusters with Palatal, the universally less marked singletons, [m, f], survived, though this was more prominent in Sonorants across age groups than in Obstruents. In [ðʝ], voicing adds to the structural complexity, given that Palatal [ç] (in onset [fç]) is acquired faster than Palatal [ʝ] (in onset [ðʝ]) (Table 2). Note that adult [ðʝ] never surfaces in our data substituted by [θç]. This suggests that coronal interdental fricative is marked in C1 position, though Labial fricative /f/ in [fç] is not. It is known that /f/ is typically less marked than /θ/ cross-linguistically (e.g., Ingram & Babatsouli, 2024). Note also that reduction to [ð] for onset [ɣð] is the least preferred member. We argue that because of interdental as C1 in word-initial onset, [ðʝ] is the slowest developing branching onset in our data, which explains the developmental variability in headedness evidenced in its reduction patterns. Figure 2 shows cyclicity in the reduction patterns whereby reduction to [ð] dominates in the youngest group and in the age group (3;0–3;6), but not in the other two age groups, and is markedly not acquired yet by age 3;6–4;0 (Table 2). We conclude that this initial branching onset is still developing in our data, which is why so much variability reduction occurs.

4.3.2. Single Member Substitutions (Not Adult-like)

With regard to not adult-like productions, our observations reveal patterns, such as stopping and fronting to Coronal, evidenced in early developing grammars.

i. The majority of substitutions are instigated by manner changes to unmarked coronal stops, which comprises mostly plosives (3), but also two instances of the voiced affricate (4, 5).

(3) [ftɛɾɐ]→[dɐdɐ] redublication, regressive assimilation to /ɾ/ substitution
(4) [fçoɡo]→[dzodzo] redublication, stopping
(5) [ðʝɐvɐzi]→[dzɐdzɐtsi] regressive assimilation to coronal substitution [ts] for /z/

ii. Another manner change involves substitutions of coronal obstruents by coronal sonorants (6, 7).

(6) [ftɛɾɐ]→[lɐlɐ] redublication, regressive assimilation to lateral of /ɾ/ substitution
(7) [xtɛnɐ]→[nɛnɐ] redublication, regressive assimilation to /n/

iii. There is a single instance of coalescence to coronal fricative in (8).

(8) [ftɛɾɐ]→[s] regressive assilimilation of /f/ to coronals in the word

iv. When palatals are targeted, the overwhelming number of substitutions are also palatal, as in [c] for [ç].

5. Limitations of the Study

Our study focused on preschool-aged children, meaning that some clusters were still developing. We hope to investigate the development of these clusters in older children in the future. Other limitations of the study stem from the composition of the participant groups. The sample size may limit the broader applicability of the findings. Additionally, some parents declined consent due to concerns about the test's difficulty or their child's ability to cooperate with an unfamiliar examiner. Even among those with guardian consent, certain children opted out of participation due to discomfort or anxiety related to the testing environment. Consequently, the participants may not fully represent the general population and could display traits such as greater sociability or more advanced speech skills. Finally, the children's ability to produce individual consonants (singletons) independent of clusters is not reported in this study. If this had been included, it would have helped elucidate the interpretation of their cluster production patterns.

6. Conclusions

This article has reported the results of a cross-sectional study that investigated the developmental patterns of Greek-specific clusters (word-initial and word-medial CC onsets) that comprise level and falling sonority Obstruent + Obstruent members, and level sonority Nasal + Nasal members. Our data were elicited using PAel (Babatsouli, 2019; Babatsouli & Geronikou, 2022), a word-list elicitation task that tests these clusters in the following word types: *φτερά* [ftɛ.ˈɾɐ] "feathers"), *χτένα* [ˈxtɛ.nɐ] "comb" and *νύχτα* [ˈni.xtɐ] "night", *φθινόπωρο* [fθiˈno.po.ɾo] "autumn", *φιόγγος* [ˈfço.gos] "ribbon", *ζωγραφιά* [zo.ɣɾɐ.ˈfçɐ] "drawing", *διαβάζει* [ðʝɐ.ˈvɐ.zi] "reads", *κλειδιά* [kli.ˈðʝɐ] "keys", *χθες* [ˈxθɛs] "yesterday", *ραβδί* [ɾɐ.ˈvði] "stick", *γδέρνει* [ˈɣðɛɾ.ni] "scratches", *μοιάζουν* [ˈmɲɐ.zun] "resemble", and *λίμνη* [ˈlim.ni] "lake". The 90 Greek-speaking monolingual children in our study, aged between 2;0 and 4;0, had only acquired clusters [ft], [fç], and [mɲ] at the 80%-90% acquisition level, but not the rest. Most clusters in the obstruent + obstruent category reduced to their second member, while nasal + nasal clusters reduced to their first member. We have found that the decrease in reductions for individual clusters reflects by-and-large their acquisition paths longitudinally. Further, while average reduction varies with age, clusters tend to reduce to the same member, except for [ðʝ]. Our results constitute a quantitative report on developing clusters along the span of phonological development and contribute to qualitative interpretations of cluster reduction and simplification patterns in Greek-speaking children's typically developing speech. In interpreting the children's productions of these under-researched cluster types cross-linguistically and in Greek, we have identified a veiled sonority effect which has not been reported before in the literature. The findings carry relevant implications for guiding the assessment and intervention of atypically developing child speech but also enhance the understanding of how clusters develop in child speech cross-linguistically.

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