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ARTICLE

Acquisition of the feature [+spread glottis] in Icelandic

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Abstract

The feature [+spread glottis] ([+s.g.]) denotes that a speech sound is produced with a wide glottal aperture with audible voiceless airflow. Icelandic is unusual in the degree to which [+spread glottis] is involved in the phonology: in /h/, pre-aspirated and post-aspirated stops, voiceless fricatives and voiceless sonorants. The ubiquitousness of the feature could potentially affect the rate and process of its acquisition. This paper investigates the development of [+s.g.] in Icelandic, both in general and in a range of contexts, in a cross-sectional study of 433 typically developing Icelandic-speaking children aged two to seven years. As a feature, [+s.g.] is acquired early in Icelandic, although specific sound classes lag behind due to other output constraints. Children reach mastery of [+s.g.] by age three except in word-initial post-aspirated stops and voiceless nasals. Findings are interpreted in light of the literature on the feature and its development.

Keywords: phonological development; phonological acquisition; phonological disorders; speech disorder; spread glottis

Introduction

The laryngeal feature [+spread glottis] (henceforth [+s.g.]) is unusually prevalent in Icelandic. It is interesting as a feature to study in acquisition as it is involved in a large number of consonant contrasts, some of which are unique for European languages and rare across languages. This articulatorily defined phonological feature, a part of most feature theories since Halle and Stevens (1971), characterizes speech sounds in which the vocal folds are actively separated, with somewhat diverse relationships to the timing of other articulations. In speech sounds that require continuous airflow — fricatives and sonorants (nasals, liquids, glides, [h], vowels) — vocal fold separation is the only means of achieving voicelessness. This gives rise to a certain analytical ambiguity as to the relative role of the features [+s.g.] and [-voice] in the phonological patterning of voiceless phones like [f], [s], [n̥], [r̥] and [h] (Vaux, 1998; Nicolae & Nevins, 2016).

In stops, where oral and nasal airflow is blocked, the feature [+s.g.] is generally manifested as aspiration: by timing the peak of the glottal opening gesture at or near the release or (less commonly) the onset of oral closure, an audible period of voiceless airflow results after the stop (post-aspiration, e.g., [t^h]) or before it (pre-aspiration, e.g., [^{h}t] or [ht]). Icelandic exhibits some crosslinguistically uncommon [+s.g.] categories: voiceless sonorants (e.g., [n̥]) and pre-aspirated stops (e.g., [hp]). Maddieson (1984), reporting on a balanced sample of 317 languages, stated that while voiceless fricatives are very common (274 languages), as are /h/ (202) and post-aspirated stops (82), few languages in the sample have voiceless nasals (11), voiceless liquids (10) or pre-aspirated stops (2). None of the languages in the sample had both pre-aspirated stops and voiceless nasals/liquids.

The feature [+s.g.] is central to Icelandic phonology, in terms of the numerous phonemic [±s.g.] contrasts, the frequency and diversity of [+s.g.] phones, and productive sound patterns referencing [+s.g.]. The question is how such an unusually ubiquitous feature is acquired. The current study examines the acquisition of the feature [+s.g.] across various contexts in typically developing (TD) monolingual Icelandic-learning children. The following introduction outlines key background information on Icelandic phonology, previous research on the acquisition of [+s.g.], and the sound classes containing it.

This paper has a data-oriented focus, and is not intended to evaluate the relative adequacy of different theories, though it does address some relevant issues. We presuppose a non-linear constraints-based phonological approach such as that of Bernhardt and Stemberger (1998), which has its roots in phonological theory, phonetics, and language processing. A crucial part of such approaches is that sub-segmental characteristics (for which we use the term FEATURES) are joined together into segments, and both levels co-exist in the representation (along with larger groupings of elements). This approach shares with other approaches the idea that the frequency of elements (both features and segments) influences acquisition, with a tendency for high-frequency elements to develop earlier than low-frequency (e.g., Beckman & Edwards, 2010). This approach also shares many characteristics with Articulatory Phonology (reviewed in Namasivayam et al., 2020), with a similar view of the specific issues relating to laryngeal gestures and how they are combined with supralaryngeal gestures. In practice, sub-segmental elements such as features (and laryngeal gestures) have gotten less attention than segments (and supralaryngeal gestures), and this paper explores the consequences of an unusually widespread laryngeal feature.

Consonants

The Icelandic consonant inventory (Supplemental File 1) consists of 24 consonants, traditionally divided into stops /p^h, p, t^h, t, c^h, c, k^h, k/, fricatives /f, v, θ, ð, s, ç, j, ɣ, h/, nasals /m, n, n̥/, laterals /l, l̥/, and rhotics /r, r̥/ (Árnason, 2005). The voiced "fricatives" /v, ð, j, ɣ/ are generally realized as approximants [ʊ, ð̞, j, ɯ] (Helgason, 1993), with velar /ɣ/ and dental /ð/ sometimes so weakly articulated, especially intervocalically, as to be imperceptible (*toga* [ˈtʰɔːɯa]~[ˈtʰɔː.a] 'pull'; *maður* [ˈmaːð̞ʏr]~[ˈmaː.ʏr] 'man').

The majority of consonants are voiceless (16 of 24) and nearly all consonants are paired with respect to either aspiration (in stops, e.g., /p^h/ vs. /p/) or voicing (in fricatives and sonorants, e.g., /f/ vs. /v/, /n̥/ vs. /n/). The unpaired voiced consonants /m/ and /ɣ/ have voiceless allophones ([m̥], [x]) in certain environments, and the dorsal allophones of /n/ ([ɲ, ŋ], by assimilation to a following palatal or velar stop, respectively) likewise have

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voiceless variants ([n̥, ŋ̥]). Bombien (2006) reports that /h/ is breathy voiced between vowels, i.e., voiced but still [+s.g.]. The only consonants that have no simply voiced counterparts are /s/ and /h/.

Word structure

With few exceptions, lexical stress falls on the word-initial (WI) syllable. Because stressed syllables must be heavy, stressed vowels (including diphthongs) are predictably long (bimoraic) or short (monomoraic), depending on context (Árnason, 2011): long in open syllables (*fela* [ˈfɛːla] 'to hide', *sötra* [ˈsœːtra] 'to sip') and before a single word-final (WF) consonant (*glas* [klaːs] 'glass'), but otherwise short (*borg* [pɔrk] 'city', *faldi* [ˈfal.tɪ] 'he/she hid'). Unstressed vowels are always short. Intervocalic or WF consonants may be long (geminate, i.e., moraic), cf. *bollur* [ˈpɔlːʏr] 'buns' vs. *bolur* [ˈpɔːlʏr] 't-shirt', *kinn* [cʰɪnː] 'cheek' vs. *kyn* [cʰɪːn] 'gender'.

The feature [spread glottis]

Icelandic sound patterns (lexical contrasts, phonotactics) involving [s.g.] are more extensive than any of the languages in the Maddieson (1984) database.[1] We treat [s.g.] as a binary feature, describing segments as [+s.g.] or [-s.g.], though this matters little for our purposes. The phonetic manifestation of [+s.g.] is ASPIRATION in stops and VOICELESSNESS in fricatives and sonorants. The view that voicing contrasts and voicing alternations in the latter involve [s.g.] rather than [voice] is standard in phonological analyses of Icelandic (e.g., Thráinsson, 1978; Ringen, 1999; Árnason, 2011).

As noted, [s.g.] is contrastive in stops, e.g., [+s.g.] /pʰ/ vs. [-s.g.] /p/. The unaspirated [-s.g.] stops (orthographically usually *b*, *d*, *g*) are voiceless [p, t, c, k], even intervocalically (and not [b̥, d̥, ɟ̊, g̊] as in English or German; e.g., Jessen & Ringen, 2002). As a manifestation of [+s.g.] in stops, POST-ASPIRATION (e.g., [tʰ]) can only occur syllable-initially and, except for certain northern dialects, is generally restricted to root-initial (usually word-initial) position; e.g., *vika* 'week' is [ˈvɪːka] for most speakers and [ˈvɪːkʰa] only in the North (Jónsson, 1994; but see Árnason, 2011: 104–105).

PRE-ASPIRATION is also frequent: [+s.g.] stops can appear as an [h]-stop sequence in certain environments, primarily before /l, n/ or where the orthography has a doubled stop (Thráinsson, 1978; Árnason, 1986), e.g., *epli* [ˈɛhplɪ] 'apple', *detta* [ˈtɛhta] 'fall'. (Historically, pre-aspirated stops were geminates.) Phonetic studies agree that pre-aspiration is considerably longer than post-aspiration, similar in duration to the segment [h] (Heimisdóttir, 2015), and with a closure duration similar to clusters like [ft] or [sk]. Pre-aspirated stops in Icelandic are therefore standardly transcribed as e.g., [ht] rather than [ʰt]. Consistent with this transcription, most analyses treat pre-aspirated stops as bisegmental (clusters), but view the [ht] vs. [tː]/[t] difference as reflecting phonemic (underlying) [+s.g.] vs. [-s.g.] in the stop and hence continue to use the term "pre-aspiration". Some, however, contend that [ht] is not a true cluster (e.g., Hoole & Bombien, 2010; cf. Lodge, 2007). Combined with vowel length as discussed above, there is a three-way surface distinction between [V:C], [VC:], and [VhC].

[1]Although morphology plays a role relative to [+s.g], we focus on morpheme-internal patterns for simplicity and brevity.

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Fricatives and sonorants generally show a VOICELESS vs. VOICED contrast in word-initial (root-initial) position, e.g., *fara* [ˈfaːra] 'go' vs. *vara* [ˈvaːra] 'warn', *hlýða* [ˈl̥iːða] 'obey' vs. *líða* [ˈliːða] 'feel', *hnefi* [ˈn̥ɛːvɪ] 'fist' vs. *nefi* [ˈnɛːvɪ] 'nose (DAT.SG)'. Phonetically, [l̥, r̥] have more turbulent airflow than the voiceless nasals and may sound weakly fricated. WI voiceless sonorants often have a voiced offset ([ˈn̥̍n], etc.), leading some to suggest that WI [n̥, l̥, r̥] might be analyzed as clusters, /hn, hl, hr/ (Haugen, 1958; Thráinsson, 1981; but see Jessen & Pétursson, 1998). What matters here is that these WI onsets involve [+s.g.], realized as vocal-fold spreading superimposed on the articulatory configurations of [n, l, r].

Fricatives and sonorants also appear to display a voicing contrast in word-medial (WM) and WF clusters when followed by a stop, e.g., *panta* [ˈpʰan̥ta] 'order' vs. *panda* [ˈpʰanta] 'panda', *orka* [ˈɔr̥ka] 'energy' vs. *orga* [ˈɔrka] 'howl', *liðka* [ˈlɪθka] 'loosen' vs. *ryðga* [ˈrɪðka] 'rust'. This is generally understood as DEVOICING by relocation (spreading) of [+s.g.] from the stop onto the preceding consonant (Thráinsson, 1978; Ringen, 1999; Árnason, 2011), and resembles pre-aspiration (overlap of [+s.g.] with a preceding vowel; Hoole & Bombien, 2010). The rhotic /r/ and non-coronal fricatives /v, ɣ/ devoice before [+s.g.] fricatives and sonorants, e.g., *morfín* [ˈmɔr̥fin] 'morphine', *lagfæra* [ˈlaxfaira] 'adjust', *rafhlaða* [ˈraf̥l̥aða] 'battery' (cf. *rafbók* [ˈravpouk] 'e-book'). By contrast, nasals, /l/ and /ð/ remain voiced in that environment, e.g., *dans* [ˈtans] 'dance', *alfa* [ˈalfa] 'alpha', *boðhlaup* [ˈpɔðl̥øyp] 'relay race'.

In other WM contexts (besides the aforementioned cluster types), voiceless sonorants and fricatives other than /s/ are uncommon, except in compounds (e.g., *hesli#hneta* [ˈhɛstlɪˌn̥ɛːta] 'hazelnut'). Intervocalic voiceless [f] is largely limited to loanwords or proper names, though many are frequent (*sófi* [ˈsouːfɪ] 'sofa', *kaffi* [ˈkʰafːɪ] 'coffee'). Intervocalically, [θ] is rare, and /h/ and voiceless sonorants essentially unattested.

WF fricatives and certain sonorants show UTTERANCE-FINAL DEVOICING: *haf* /hav/ [haːf] 'ocean', *búð* /puð/ [puːθ] 'shop', *lag* /laɣ/ [laːx] 'song'. Although /v, ð, ɣ/ are typically approximants [ʋ, ð̞, ɰ], their pre-pausal voiceless realizations are true fricatives (e.g., voiceless [f], not [ʋ̥]) indicating that the devoicing is phonological rather than phonetic. We note also that WF /ɣ/ in some words, especially after a rounded vowel, can be absent in pre-pausal contexts, e.g., *skóg* [skouː] 'forest (ACC)' and *mág* [mauː] 'brother-in-law (ACC)'. Thus, children might analyze these words as not containing /ɣ/ (/skou/, /mau/). While WF liquids devoice word finally, WF nasals do so only after a voiceless consonant, e.g., *vagn* [vakn̥] 'wagon' vs. *tún* [tʰuːn] 'field'. WF devoicing is limited to pre-pausal position, phrase-internally, a WF fricative or sonorant remains voiced even if a [+s.g.] consonant follows, e.g., *búð fyrir* [ˈpuːð̞ fɪrɪr] 'a shop for', *bíl til* [ˈpiːl tʰɪl] 'a car (ACC) to'.

Development of [+spread glottis] crosslinguistically

The focus of most studies of phonological development is on acquisition of whole segments, rather than their composite features, and all instances of a single feature are rarely examined for consistency across different segments. To our knowledge, no study has singled out the feature [+s.g.] in phonological development, though many address voiceless fricatives or post-aspirated stops as whole segments.

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Babbling and early words

Early babbling shows a relatively high proportion of glides (vowel-like oral articulations) and glottals ([ʔ, h]; Vihman et al., 1986). Although canonical babbling and early words show shifts towards some true consonants, [h] continues to be frequent across diverse languages (Oller, 1980). Icelandic has not been included in those studies. Spreading the glottis for [h] is relatively simple and unaffected by factors like glottal tension or air pressure control necessary for oral consonants, so in principle should be combinable with any supraglottal articulation.

Later phonological development

Crosslinguistic comparisons of phonological development are challenging because of methodological differences across studies in sampling methods and sizes, criteria for mastery, etc. Furthermore, most studies report accuracy of segments rather than features, and may consider phonetic details (e.g., exact tongue placement) relevant or irrelevant to assignation of segmental mastery. For example, Smit et al. (1990) treat dentalized [s̪] (lisp) as a mismatch in English, possibly because interdental /θ/ and alveolar /s/ contrast in the language, but Beers (1995) and Fox and Dodd (1999) treat such productions as matches, taking the perspective that such phonetic detail is not important for acquisition, especially given the high prevalence of lisping. In both cases, [+s.g.] was accurate, whether or not the /s/ was dentalized. The accuracy of [+s.g.] is the important result for the current study and showed: (1) that at least some features develop independently of the segments in which they appear; and (2) that certain phonetic details may be ignored when evaluating aspects of phonological acquisition.

Comparing across languages also highlights one drawback of a convention used in research in phonological development: the child's pronunciation is given between phonetic square brackets (e.g., *me* [miː]), while the adult target is given between phonemic slashes (/miː/). We want to treat WI aspirated stops in Icelandic, English, and other Germanic languages as comparable challenges for young children, even though the aspiration is phonemic for Icelandic adults (e.g., both [pʰ] and /pʰ/) but standardly taken as allophonic for the other Germanic languages (so [pʰ] but /p/). Children must master WI aspiration whether it is contrastive or allophonic. Rice (1996) and Rose and Inkelas (2011) resolve this conflict by placing adult-like target forms between vertical bars: e.g., |miː|, |pʰaɪ|. We will follow that convention here, reserving phonemic slashes for adult phonemic representations.

Summarizing across Germanic languages (not including Icelandic), WI |h| is acquired by 3;0 in most languages (McLeod & Crowe, 2018), while all other segment types with [+s.g.] are later acquired. For post-aspirated stops, mean age of acquisition for English is reported to be around 3;6 (Dodd et al., 2003; Smit et al., 1990), but in German 1;6–2;11 (Fox & Dodd, 1999) and Danish 2;0–2;5 (Clausen & Fox-Boyer, 2017), possibly reflecting differences in criteria for mastery and whether researchers explicitly paid attention to aspiration. For voiceless fricatives, the mean age of acquisition (reported ≥90% mastery; whereas 75% accuracy is regarded as a criterion for full acquisition) appears to be (even later around 4;4 years for grooved sibilants). However, details are not provided for the feature [+s.g] itself in any of the studies.

Acquisition of [+s.g.] has not been specifically studied in Icelandic, although some information is available from match and mismatch data in other studies. Gíslason et al. (1986) examined phonological development of 200 children longitudinally at ages four

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and six years, aggregating data by segment types across word positions. By age four, mastery of [+s.g.] was observed for the following segment types (even if, in very few instances, place or manner features were still developing): (1) voiceless fricatives, mismatches usually being other [+s.g.] fricatives; and (2) pre-aspirated stops (<3% of the children showed [-s.g.] mismatches overall; 5.9% for |hk|). The remaining categories showed later mastery of [+s.g.]: (3) post-aspirated stops, generally mastered by age four, but occasionally realized as [-s.g.] unaspirated stops; (5) |n̥|, often produced as [+voi, -s.g.] [n] (36.6% of four-year-olds, 23.4% of six-year-olds). Specific mismatches for |l̥, r̥|, were not reported. For voiceless sonorants in WM and WF clusters, the level of accuracy seemed to reflect the complexity of the cluster and target word. Clusters with a voiceless nasal or lateral had higher mean accuracy (87.6%, age four; ≥90%, age six) than those with voiceless rhotics (58.9%, age four; 86.8%, age six).

In a later study of earlier development, Másdóttir (2008) reports longitudinal data for 28 TD children (at ages 2;4 and 3;4), and nine children with protracted phonological development (PPD) (age 4;1–5;5), using structured play and picture-naming. WI and WM singleton consonants and clusters were examined. Results (Table 1) generally aligned with Gíslason et al. (1986).

Note that Table 1 presents full segmental matches, not just matches for [+s.g.]. Many productions retained [+s.g.], however, with mismatches frequently affecting place features (e.g., |hk| → [ht]). Earliest-mastered were WI |h|, WI post-aspirated stops and WM pre-aspirated stops. At 2;4, pre-aspirated stops |hp, ht, hc, hk| were 20% more accurate than pre-aspirated stop + |l| clusters |hpl, htl|, possibly reflecting the greater complexity of the clusters. Non-WF voiceless fricatives showed >75% match at 3;4, but WF fricatives lagged behind. WM voiceless sonorants (in sonorant-stop clusters) had less than 70% accuracy at age 3;4; WM |l̥| + stop clusters had higher accuracy levels at both ages than did |r̥| + stop clusters (2;4: 23.13% and 7.14%, 3;4: 73.01% and 65.55%, respectively).

Both studies discussed report gradual acquisition of [+s.g.] segment types by age. However, they focused on segments rather than the feature [+s.g.], and it is not always clear whether manner or place features were the cause of the mismatches, rather than [+s.g.].

Table 1. Mean (SD) % accuracy/match for [+s.g.]-containing segments in TD children at ages 2;4 and 3;4 (Másdóttir, 2008)

Segmental type and word position	2;4 (*n*=28) %	3;4 (*n*=28) %
WI |h|	74.3 (30.1)	**96.2 (5.5)**
WI post-aspirated stops |p^h, t^h, c^h, k^h|	50.3 (39.4)	**93.5 (12.7)**
WM pre-aspirated stops |hp, ht, hc, hk, hpl, htl|	73.8 (30.4)	**92.6 (9.0)**
WI voiceless fricatives |f, ç, s, θ|	45.7 (36.9)	73.6 (30.1)
WM voiceless fricatives |f, s|	62.1 (33.9)	75.8 (27.2)
WF voiceless fricatives |θ, s, x|	36.9 (36.3)	49.7 (35.2)
WI voiceless sonorants |l̥, n̥, r̥|	Insufficient data	Insufficient data
WM voiceless sonorants |l̥p, l̥t, l̥c, l̥k, r̥p, r̥t, r̥c, r̥k|	15.1 (29.3)	69.3 (38.2)

Note. WI = word-initial; WM = word-medial; WF = word-final. **Boldface indicates mastery.**

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The present study

The acquisition of the feature [+s.g.] is of special interest for Icelandic because of its unusually wide distribution across manner categories. The fact that [+s.g.] is present and common early on indicates knowledge of how to articulate it and a solid base for generalization to new speech sounds. The child nonetheless needs to learn how to output [+s.g.] with a variety of supraglottal articulations: (1) in competition with more frequent features such as [+voice] (and [-s.g.]) for nasals and liquids; (2) in contexts with unusual timing for the [+s.g.] element (i.e., aspiration); or (3) when it is an enhancement feature (as for fricatives).

For the present study, we are interested in the dispersion of the feature [+s.g.] throughout children's phonological systems. Is there a coherence to the development of [+s.g.]-containing segments such that the feature provides some unity among these disparate categories? Extrapolating from the [+s.g.] data, how does development of individual features relate in general to acquisition of segments? Research on the development of individual features goes back at least to Jakobson (1968/1941), but tends to focus on place and manner features.

Crosslinguistic trends and previous research findings led to a number of predictions:

1. Age: Significantly higher match levels were expected gradually by age, for the feature [+s.g.] itself and in its various combinations with other features.
2. Segmental categories: Voiceless fricatives and sonorants were predicted to be later-acquired than |h| and pre- and post-aspirated stops, with certain qualifications:
   (a) Following Gíslason et al. (1986), post-aspirated stops were expected to be later-acquired than |h| and pre-aspirated stops;
   (b) voiceless fricatives were expected to show mastery by age three;
   (c) voiceless nasals were expected to be later-acquired than other voiceless sonorants.
3. Mismatch for segment, match for [+s.g.]: A segment may not match the target, but nonetheless may match for [+s.g.]. If [+s.g.] is earlier-acquired than other features in the segment, the most frequent mismatches may include [+s.g.], e.g., [h] for other segments, post-aspirated stops for fricatives, and even pre-aspirated stops for post-aspirated stops and voiceless sonorants for other unmastered speech sounds.
5. Mismatches for segments and [+s.g.]: If both the segment and [+s.g.] are mismatched, expected mismatches would include:
   a. Deletion of the syllable or segment or, for the stops, aspiration (whether pre- or post-). At earlier ages, complexity constraints were expected to result in cluster reduction, with deletion of the [+s.g.] segment. Later on, other [+s.g.] substitutions were expected, as above;
   b. Pre-aspirated stops: If [+s.g.] is to be maintained, pre-aspirated stops might be replaced by geminate [-s.g.] stops or the preceding vowel might be lengthened;
   c. [-s.g.] (and [-voice]) replacement: unaspirated stops or voiced glides for fricatives or sonorants, aspirated stops; voiced sonorants for voiceless ones.

Method

Ethical approval

Approval for this study was obtained by Persónuvernd (The Data Protection Authority, Iceland; S5266/2011) and municipalities across Iceland. Preschool directors and children's parents gave consent for the children to participate.

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Participants

The data for this study come from a normative database of 433 monolingual Icelandic-speaking children aged 2;6 to 7;11 years (Másdóttir, 2014; see Másdóttir et al., 2021 for details). There were six age groups: age two years (n = 34), three (n = 112), four (n = 105), five (n = 88), six (n = 49), and seven (n = 45). All groups had a 12-month range (e.g., 4;0-4;11), except the youngest group (2;6-2;11). Children with cleft lip/palate, developmental disorders (e.g., Down syndrome, autism), or a moderate or greater hearing loss were excluded.

Procedures

The data were collected 2011–2013. Two certified speech-language therapists (SLTs) and six trained SLT master's students, all Icelandic-speaking, tested the children using a standardized Icelandic phonology test, Málhljóðapróf ÞM [ÞM's Test of Speech Sound Disorders] (Másdóttir, 2014): a picture-naming test, assessing 47 single consonants and 45 consonant clusters in three word positions. Each child was tested individually in a quiet room in their school following standardized procedures (Másdóttir, 2014). In the few cases where spontaneous productions were not elicited, imitative utterances were accepted. Recordings were made with a Sony MiniDisc Recorder (MZ-R30) using a multidirectional Sony Condenser Stereo microphone (ECM-DS70P) or an Olympus Digital Voice Recorder WS-81 (sampling rate of 44,100 Hz, stored uncompressed).

For the current study, 63 words containing the target [+s.g.] feature were extracted for analysis, 11 of which included two [+s.g.] segment types (see Appendix 1). A total of 34,683 tokens were analyzed, with a range of 1,384–6,061 tokens for the different [+s.g.] consonant types: (a) WI /h/, (b) WI post-aspirated stops, (c) WM/WF pre-aspirated stops, (d) WI/WM/WF voiceless fricatives, and (e) WI/WM/WF voiceless sonorants.

The segment types differed somewhat by word position context, reflecting Icelandic phonotactics. Post-aspirated stops and |h| occur only word-initially, and pre-aspirated stops only word-medially and -finally. Voiceless fricatives occur across word positions and are similar across those positions. Voiceless sonorants, however, vary across word positions: word-initially, they contrast as singleton phonemes with their voiced counterparts (e.g., *hjól* |ɕou̥ːl̥| 'bicycle' vs. *jól* |jou̥ːl̥| 'Christmas'); word-medially, they appear only in clusters; but word-finally, they can occur as singletons or in clusters, but have no voiced counterparts. An attempt was made to balance the number of words for each segmental type, i.e., two words minimum per phoneme for each category, with a few exceptions where data were not available. See Appendix 1 for target words.

The data were transcribed by the first author and three other SLTs with extensive phonetic transcription experience (see Másdóttir et al., 2021). Transcription reliability was conducted by a native Icelandic speaker with a degree in linguistics who is a practicing SLT. Inter-rater reliability, conducted for 10% of participants in each age group (the full samples for 45 children total) was 95.8% (12,420 data points for consonants), an acceptable level (Shriberg & Lof, 1991). Most discrepancies did not concern the target feature [+s.g], involving /s/ distortion, presence or absence of WI glottal stops vs deletions, and characterization of /r/ ([r]/[ɻ̥]/[ɾ]). Discrepancies were discussed until consensus was reached.

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Analysis

Phon 3.2.0 (computerized analysis: Hedlund & Rose, 2020; https://www.phon.ca) results were exported to Microsoft Excel 16.46 and LibreOffice 6.4.7.2 for quantitative analysis and then to SPSS Inc (2022, version 29.0) to complete descriptive and inferential analyses. To address research aim one (accuracy of production within different age groups), the accuracy of [+s.g.] was calculated within each of the segmental categories (e.g., |h|, voiceless nasals, etc.): 2;6-2;11, 3;0-3;11, 4;0-4;11, 5;0-5;11, 6;0-6;11, and 7;0-7;11. Research aim two (development of each [+s.g.] category as children age) was addressed using non-parametric statistical tests due to the non-normal distribution of the data: (1) Kruskal-Wallis tests with Bonferroni correction for examining age-related changes in the accuracy of [+s.g.] for each segmental category; and (2) post-hoc Mann-Whitney U tests with Bonferroni correction, to identify statistically significant differences.

Results

Results first describe overall match levels (accuracy) for the feature [+s.g.] itself and the segmental categories where [+s.g.] appears. Subsequent sections provide details on each category, including descriptions of mismatches that retain or lose the [+s.g.] feature.

Match levels for [+s.g.] and segmental categories where it appears

Figure 1 shows overall match (accuracy) by age for the feature [+s.g.], and Table 2, the match for [+s.g.] only within each segmental category by age.

As expected, Figure 1 shows that [+s.g.] was near-mastery even for the youngest age group, reaching full mastery (>90%) at age four years. In comparison, full segmental match (FSM) showed lower mean accuracy for the younger age groups, but reached mastery (>90%) about a year later, at age five.

Looking at [+s.g.] within segmental categories (Table 2), for the youngest age group, [+s.g.] was least accurate in WI post-aspirated stops (78%) and WI voiceless nasals (18%).

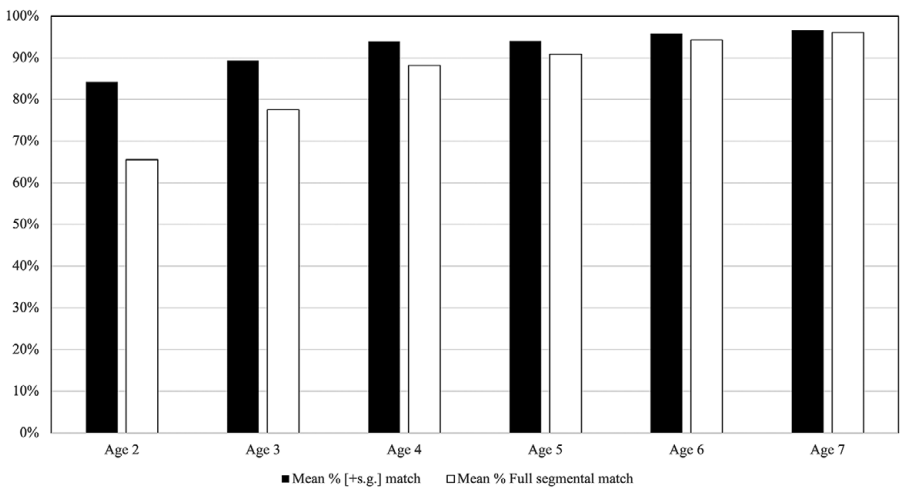

Figure 1. Mean % [+s.g.] and full segmental match across categories (averaged within and then across children within an age group).

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Table 2. Accuracy of [+s.g.] by segmental category and age group, with Kruskal-Wallis statistics for age and category comparisons

	Accuracy of [+s.g.] within segmental category by age (Mean proportion, SD)						*H, p* values: Kruskal-Wallis
Segmental category	2;6–2;11	3;0–3;11	4;0–4;11	5;0–5;11	6;0–6;11	7;0–7;11	
WI |h|	0.99 (0.03)	1.00 (0.02)	1.00 (0.01)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	$H(5) = 9.39$, $p = 0.095$
WI post-aspirated stops	0.78 (0.35)	0.90 (0.25)	0.99 (0.08)	1.00 (0.03)	1.00 (0.01)	1.00 (0.00)	$H(5) = 78.88$, $p < 0.001$*
WM/WF pre-aspirated stops	0.94 (0.19)	0.97 (0.14)	0.99 (0.05)	0.99 (0.07)	0.99 (0.04)	1.00 (0.00)	$H(5) = 14.20$, $p = 0.14$
WI voiceless fricatives	0.96 (0.06)	0.98 (0.07)	1.00 (0.01)	1.00 (0.01)	1.00 (0.00)	1.00 (0.00)	$H(5) = 73.94$, $p < 0.001$*
WM voiceless fricatives	0.97 (0.15)	0.98 (0.12)	1.00 (0.00)	1.00 (0.02)	0.98 (0.14)	1.00 (0.00)	$H(5) = 7.93$, $p = 0.16$
WF voiceless fricatives	0.90 (0.11)	0.96 (0.08)	0.98 (0.05)	0.99 (0.04)	1.00 (0.02)	1.00 (0.00)	$H(5) = 78.15$, $p < 0.001$*
WI voiceless nasals	0.17 (0.39)	0.26 (0.44)	0.43 (0.50)	0.40 (0.49)	0.57 (0.50)	0.62 (0.49)	$H(5) = 31.54$, $p < 0.001$*
WI voiceless liquids	0.92 (0.18)	0.93 (0.22)	0.98 (0.13)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	$H(5) = 25.42$, $p < 0.001$*
WM voiceless sonorants	0.86 (0.22)	0.96 (0.15)	0.99 (0.07)	1.00 (0.03)	1.00 (0.00)	1.00 (0.00)	$H(5) = 69.61$, $p < 0.001$*
WF voiceless sonorants (singleton)	0.85 (0.17)	0.95 (0.12)	0.99 (0.05)	0.99 (0.08)	1.00 (0.02)	1.00 (0.00)	$H(5) = 95.17$, $p < 0.001$*
WF voiceless sonorants (cluster)	0.88 (0.27)	0.95 (0.16)	0.99 (0.07)	0.98 (0.10)	1.00 (0.00)	1.00 (0.00)	$H(5) = 21.16$, $p < 0.001$*
OVERALL	0.84 (0.93)	0.89 (0.09)	0.94 (0.05)	0.94 (0.05)	0.96 (0.05)	0.97 (0.04)	

Note. WI: word-initial; WM: word-medial; WF: word-final

Accuracy gradually increased reaching 100% accuracy in post-aspirated stops by age five years, and all categories except voiceless nasals (62%) by age seven years.

Kruskal-Wallis tests were performed to examine differences in the accuracy for the 11 [+s.g.] features between the six different age groups. Age differences were significant (Kruskal-Wallis tests, $p < .001$) except for |h|, pre-aspirated stops and WM voiceless fricatives. Mann-Whitney *U* tests (also with Bonferroni correction) were used for post-hoc comparisons of [+s.g.] in segmental categories where associations remained significant after Bonferroni correction had been applied. The 2-year-olds and 3-year-olds differed significantly from other age groups with some exceptions (Supplemental File 5). For WI voiceless fricatives, all age comparisons with 2-year-olds were significant ($p < .001$). For voiceless sonorants in WF clusters, comparisons between the 2-year-olds and 5-, 6- and 7-year-olds were significant ($p < .005$). For the remaining two categories, the following comparisons were significant: (1) for WI nasal sonorants, between 2-year-olds and 6- and 7-year-olds and also 3-year-olds and 6- and 7-year-olds ($p < .006$); (2) for WI liquid sonorants, between 2-year-olds and 5-, 6-, and 7-year-olds, and between 3-year-olds and 6- and 7-year-olds ($p < .05$); and finally, (3) for WF voiceless fricatives and WM sonorants, for 2-year-olds versus all other age groups ($p < .001$) and 3-year-olds versus 5-, 6- and 7-year-olds were significant ($p < .04$).

The subsequent sections provide more details on the various segmental categories in which [+s.g.] appears. Both match and mismatch data are presented in each section. Mismatches include substitutions where [+s.g] is retained (i.e., as [h], aspiration, or voiceless fricative/sonorant), versus where it is not (deletion of the segment; [+s.g.] → [-s.g.], e.g., de-aspiration). Mismatches in manner and/or place also affect FSM but are only briefly mentioned because the major focus is the feature [+s.g.]. (Supplemental Files 2-3 provide mismatch data.)

WI |h|, pre- and post-aspirated stops

These three categories are reported in the same sub-section because they concern [h] as a full segment or as aspiration. WI |h| and pre-aspirated stops were mastered early: by age two for [+s.g.] (99% and 94% match respectively), and by age three, for the full segments. However, as predicted, WI post-aspirated stops reached mastery only about a year later.

Among the eight full segmental mismatches for WI |h|, [+s.g.] matched three times, once with fricative [f] (#1). Mismatches for [+s.g.] included deletion (e.g., #2) and an unaspirated [t] (#3).

	Word	Adult	Child
(1)	*hús*	|huːs|	[fuːs]
(2)	*húsið*	|huːsɪθ|	[uːθɪ]
(3)	*hestur*	|hɛstʏr̥|	[tɛhtʏɻ̊]

For pre-aspirated stops, rare patterns that maintained [+s.g.] were cluster creation with other [+s.g.] elements (e.g., #4, #5), or coalescence (6), with both maintaining syllable timing either with a consonant substitution or (#4, #5) vowel lengthening (#6). Stops were not deleted, and neither post-aspirated stops nor voiceless sonorants replaced pre-aspirated stops.

(4)	*dúkka*	|tuhka|	[tuŋ̊ka]
(5)			[kufka]
(6)	*klukka*	|kʰlʏhka|	[kʏːxa]

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However, most commonly mismatches occurred for [+s.g.] through stop gemination (#7), maintaining consonant timing.

(7) *dúkka* |tuhka| [tukːa]

For post-aspirated stops, the most common mismatch was de-aspiration, i.e., loss of [+s.g.] (|p^h, t^h, c^h, k^h| → [p, t, c, k]) a relatively frequent pattern at age two (23% of targets), but decreasing with age (9%, age three; 0.2%, age six). Full segmental mismatches for post-aspirated stops also involved manner and/or place changes, sometimes retaining [+s.g] (#8, #9) and sometimes not (#10). Voiceless fricatives and [h] substitutions ([+s.g.] match) were rare.

(8) *koddi* |k^hɔtːɪ| [t^hɔtːɪ]
(9) *kaffi* |k^hafːɪ| [hafːɪ]
(10) [tafːɪ]

Voiceless fricatives

Match for [+s.g.] in voiceless fricatives was >90% at age two, with WF fricatives being lowest, primarily due to |x| deletion in the word *sög* |sœːx| 'saw'. Even when frication was lost, [+s.g.] was generally maintained with post-aspiration, more often word-finally (e.g., #11) than elsewhere (especially word-medially; Supplemental File 4). Pre-aspirated stops or voiceless sonorants rarely replaced fricatives (e.g., #12, or, WF |x| → [ht] in *sög*).

(11) *mús* |muːs| [muːt^h]
(12) *blása* |plauːsa| [plau̥ːa]

Word-initially, full segment mismatches for fricatives (involving place, not [+s.g.]) were primarily other fricatives and [h] at ages two (11.2% of targets; 4.7% respectively) and three (5.8%; 2.6%), decreasing further by age.

Voiceless sonorants

Voiceless sonorants (nasals/liquids) diverged developmentally (Figure 2). For nasals, [+s.g.] was later-acquired word-initially, with only 62% match for [+s.g.] even for 7-year-olds. The majority of mismatches (83%) for WI voiceless nasals at age two (and all mismatches for the 4- to 7-year-olds) were voiced ([-s.g.]) nasals, with this substitution pattern still in place for about a third of tokens at age seven. In contrast, for WI voiceless liquids, [+s.g.] showed >90% match by age two and was near ceiling by age four. For the WM voiceless sonorants (in clusters), all but the two-year-olds had >90% match for [+s.g.], although mismatches still appeared until age seven. WF voiceless liquids (as singletons and in clusters) had similarly high match levels for [+s.g.] up to age four, with singletons mastered at age five and clusters at age six.

Where [+s.g.] was retained in liquid mismatch patterns, [+sonorant] [h] (matching [+s.g.]) was a relatively common substitution, for 12.5% of WI tokens (never WM), i.e., more often than for nasals and fricatives at ages two and three. Post-aspirated stops and voiceless fricatives (matching [+s.g.]) appeared occasionally word-initially in created clusters with manner/place changes, e.g.:

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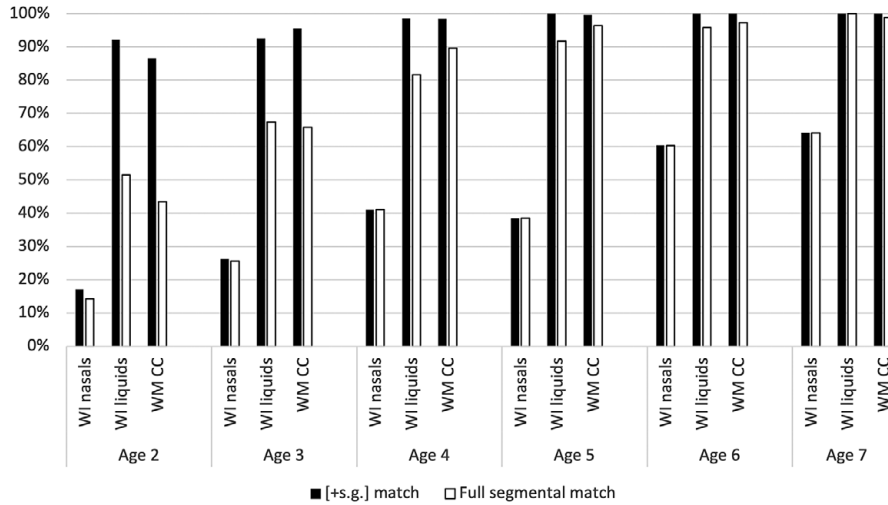

Figure 2. Percent [+s.g.] match and full segmental match for WI voiceless nasals and liquids plus WM sequences (CC) for all voiceless sonorants.

(13) *hlaupa* |l̥øyːpa| [ˈkʰl̥øyːpa]
(14) *hlaupa* |l̥øyːpa| [ˈfløyːpa]

Full segmental mismatches for liquids nevertheless usually retained [+s.g.], e.g., the common substitution [θ] for |r̥|, matching [+s.g.] and place but not manner (at age two, for 34% of WI targets; 6.5%, WM; 27.1%, WF singletons; 16.7%, WF clusters, and gradually decreasing by age, until absent at age seven). Another less frequent substitution that retained [+s.g.] but not manner and/or place was |r̥| → [l̥].

For WM and WF clusters with voiceless sonorants, [+s.g.] was often retained through substitution of a pre-aspirated stop (#15, preserving the timing units).

For voiceless liquids, loss of [-s.g.] mismatches were infrequent (unaspirated stops, voiced liquids). In WM clusters, [-s.g.] geminate stops appeared infrequently, preserving timing units but not [+s.g.] (#16). Eighteen tokens reduced to a short [-s.g.] (#17), five of these cases with compensatory vowel lengthening, preserving syllable timing but not the timing of consonants. In terms of full segments, manner and place features often mismatched at age two, and still at age seven.

(15) *bolti* |pɔl̥tɪ| [pɔhtɪ]
(16) *hjarta* |çar̥ta| [vatːa]
(17) *stelpa* |stelpan| [paːpan]

Additional observations on WM voiceless nasals versus liquids

In the above analyses, WM voiceless nasals were included with the other WM sonorants, because they appeared to act more like these than like WI voiceless nasals, in having fairly high match levels for [+s.g.]. However, WM voiceless nasals and liquids were not entirely comparable. Voiceless nasals had a higher FSM than voiceless liquids. In mismatches, voiceless liquids retained [+s.g.] more often, either in reduction of a WM cluster to a pre-

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aspirated stop or with voiceless fricative substitutions. In contrast, nasals rarely showed manner mismatches, and the WM cluster most often reduced to a [-s.g.] geminate stop at ages two and three, with too few errors at age four to test. This led to an interaction at both ages two and three, with mismatches for voiceless liquids skewed towards [+s.g.] substitutions and for voiceless nasals towards [-s.g.] substitutions. Overall, however, there was greater congruence between sonorant types (nasals, liquids) word-medially than word-initially.

Other mismatches and [+s.g.]

In terms of word structure constraints, if a consonant is deleted, [+s.g.] most likely deletes with it, even if a child might be capable of producing [+s.g.] in some other context. Consonant deletion was generally more common in younger children and for fricatives and liquids than for other segment types, affecting relative accuracy of [+s.g.] for those children and targets. Singleton voiceless liquids and fricatives and cluster elements were more likely to be deleted than entire clusters, and to a greater extent word-finally than word-initially.

Discussion

This study describes the acquisition of the feature [+s.g.] in Icelandic children from age two to seven years (n=433) overall, and in terms of its occurrence in five segmental categories (|h|, post-aspirated stops, pre-aspirated stops, voiceless fricatives and voiceless sonorants). The study focuses on the feature [+s.g.] independently and in interaction with other features, as evidenced in FSM data for the five categories and mismatch patterns in which [+s.g.] is maintained or lost. As discussed below, many of the predictions for the study were met or exceeded, with some exceptions.

Age effects for [+s.g.]: development of features versus segments

Children showed an overall match level above 75% for the feature [+s.g.] at age two (somewhat higher than expected) with increasing accuracy by age until near-ceiling, i.e., (>90%) by age four, as predicted. Within segmental categories, mastery of [+s.g.] (> 90% accuracy) was observed by age two or three for all targets but WI post-aspirated stops and WI voiceless nasals, replicating e.g., Gíslason et al. (1986). However, FSM for the various segmental categories did not occur until at least a year after mastery of [+s.g.], because of mismatches in place and/or manner features. The timing difference in acquisition of [+s.g.] versus full segments shows development of the [+s.g.] feature independent of place and manner features, especially because [+s.g.] often survived in mismatch patterns. The exceptions that did occur were generally limited to voiceless nasals and post-aspirated stops, expected based on e.g., Gíslason et al. (1986). We address those exceptions in the relevant sub-sections below.

Glottal |h|

As expected, WI |h| was mastered earlier than other [+s.g.] segments (> 90% accuracy at age two); similar to reports for other Germanic languages (Fox & Dodd, 1999; Smit et al.,

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1990) and the few mismatches that occurred were primarily deletions. Having no supralaryngeal features, |h| is the least complex of the [+s.g.] segmental types, which likely accounts for its earlier mastery.

As an early-mastered [+s.g.] segment, [h] was available to (and did) replace other segments, and also showed strong effects as expected relating to its manner features [+continuant, +sonorant], i.e., frequently replacing voiceless liquids (both [+continuant] and [+sonorant]) and voiceless fricatives (just [+continuant]) but only rarely replacing non-continuants (stops, voiceless nasals). The [h] substitutions were most frequent word-initially, and rare intervocalically, consistent with the adult distribution of singleton [h] (which occurs only word initially). The relationships between [+s.g.], manner features and word structure emphasize the interdependence between various levels of the phonology.

Pre- and post-aspirated Stops

The current study provides previously little known information about the acquisition of pre-aspirated stops (restricted to WM and WF positions in adult Icelandic). Although a crosslinguistically marked category, the feature [+s.g.] was present in over 90% of pre-aspirated targets even at age two, very slightly behind |h| but ahead of post-aspirated stops and voiceless sonorants.

Mismatches for pre-aspirated stop targets met expectations overall in terms of complexity and Icelandic phonotactics. Realization of the [h] portion as a (more complex) voiceless fricative, liquid, or nasal was rare (usually only by assimilation), and pre-aspirated stops were never fully reduced to [h] or post-aspirated stops (absent in WM and WF position in southern Icelandic). The most common mismatch was loss of [+s.g.], i.e., an unaspirated stop, occasionally a singleton (sometimes with vowel lengthening, [V:C]) but most commonly a geminate consonant ([VC:]). Adult Icelandic has complementary length, such that a stressed vowel is short before a long consonant ([VC:]) and long before a short consonant ([V:C]). If the [h] portion is lost, either the consonant or the vowel can absorb its timing, to fit prosodic restrictions on syllable timing. Target pre-aspirated stop elements [hC] are linked to consonant timing units, and the dominant output pattern maintained those links through stop gemination; re-assigning the timing unit for [h] to the preceding vowel was rare for the TD children in this study (although Másdóttir & Bernhardt, 2022, report on one exceptional case).

Post-aspirated stops were not mastered until age four, similar to (though perhaps slightly later than) the timeline for English and other languages (e.g., Fox & Dodd, 1999; Smit et al., 1990), although later than children in the smaller sample of Másdóttir (2008) for Icelandic. The feature [+s.g.] was present in fewer than 80% of outputs for post-aspirated stops at age two. Some substitutions did preserve [+s.g.] (e.g., [h], [θ]), but the most common mismatch was de-aspiration ([-s.g.]), replicating previous studies (e.g., Gíslason et al., 1986) and predictions.

The question is why post-aspirated stops were later-acquired than pre-aspirated stops, where [+s.g.] was often maintained in substitutions. Pre-aspirated stops are rare across languages, and consequently are highly marked, which might lead to expectations (following Jakobson, 1968/1941) that they should be mastered much later than the far more common post-aspirated stops. One possibility is the difference in the surface realization of pre- versus post-aspiration. Post-aspiration is realized as a short period of devoicing during a period of rapid articulatory movement, as the stop's constriction widens to reach the aperture appropriate for the following vowel. Pre-aspiration, in

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contrast, has much greater duration (in Icelandic) and is articulated essentially as a voiceless continuation of the preceding vowel (in an unchanging vocal tract); this might make it easier to produce. However, this also makes a pre-aspirated stop very similar to a bi-segmental cluster ([h]+[p]), differing only in that the feature [+s.g.] is part of (and originates in) the stop, rather than being an independent segment. Most phonologists view pre-aspirated stops of Icelandic as having been restructured into clusters, with [h] occupying the coda (see Introduction). However, unlike voiceless fricatives and sonorants, [h] does not occur as a singleton in WM or WF position and must be followed by a stop. If [hp] is a cluster, then comparison to [p^h] is not a simple locational difference concerning aspiration. For acquisition, it might be useful to examine languages that allow /h/ in codas to see what children do with WM or WF /h/-stop sequences in those languages. This may provide insight as to whether Icelandic pre-aspirated stops are actually /h/-stop clusters.

Voiceless fricatives

The feature [+s.g.] was present for voiceless fricative targets with ≥90% accuracy even at age two (including in segmental mismatches). However, as expected by their greater complexity, voiceless fricatives were mastered later than |h| by one or two years ([+s.g.] and FSM respectively).

Most substitutions for voiceless fricatives showed manner and/or place feature changes rather than [+s.g.] changes (with some deletion restricted to WF position in the word *sög*). Where [+s.g.] matched, common substitutions were [h] and post-aspirated stops, similar to other Germanic languages (Beers, 1995; Holm et al., 2022). Pre-aspirated stops, voiceless liquids and voiceless nasals were rare substitutions, as would be expected developmentally by markedness predictions.

Where [+s.g.] was not maintained, substitutions included voiced approximants (e.g., |f| as [ʋ]), but most commonly, unaspirated stops, consistent with e.g., Gíslason et al. (1986) and the fact that post-aspirated stops were later-acquired. Further, Bernhardt and Stemberger (1998) note that the function of [+s.g.] in voiceless fricatives is to enhance (the amplitude of) the frication (e.g., Kingston & Diehl, 1994); they suggest that a child who cannot yet produce fricatives may not have learned that spreading the glottis is needed to produce the amplitude of frication observed in adult speech, and so mismatch with "other" [-s.g.] speech sounds.

Voiceless liquids

Voiceless liquids comprise another uncommon category crosslinguistically and little is known about their acquisition. They are mastered relatively late in Icelandic, but mismatches generally involve manner (and sometimes place) (Másdóttir, 2018); [+s.g.] showed a high match already by age two (almost 90%).

Word-initially, [h] was the most common mismatch, though there was some tendency to voicing ([+s.g.] → [-s.g.]), more so than for fricatives (where voicing would entail a change of fricative manner to approximant, to be compatible with the adult phonology). This may represent a similarity effect, since e.g., [h] and [l̥] are both [+sonorant], while e.g., [s] is [-sonorant]. Voicing mismatches were far less common word-finally than initially.

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There were no simple instances of stopping, but a few rare mismatches where the feature [+s.g.] split off into an epenthetic segment, e.g., |l̥| as [kʰl] or [fl]. Such splitting is of low frequency in child phonology (Bernhardt & Stemberger, 1998), and previous examples with laryngeal features have involved voicing (e.g., WF /d/ as [nt]). There were some manner interchanges between the liquids (|l̥| as [r̥], |r̥| as [l̥]), but voiceless fricatives were more common substitutions, at least |r̥| as [θ], preserving target [+s.g.] and [+continuant]. This may simply reflect that most voiceless continuant consonants in Icelandic are fricatives, providing a base for generalization across similar segments. Bombien (2006) reports that Icelandic /r̥, l̥/ are slightly noisy in a way that resembles low-amplitude frication, and this may also influence the frequency of mismatches as fricatives.

Voiceless nasals

Voiceless nasals are also uncommon crosslinguistically, with little known concerning their acquisition. As expected from previous research (e.g., Gíslason et al., 1986), they were not mastered by age seven (<65% match, WI). The most common mismatch involved loss of [+s.g.] (with insertion of unmarked [+voice], e.g., |n̥| → [n], and at a higher rate than for any other [+s.g.] category). Oral stops and [h] were very rare mismatches.

Why voiceless nasals were late and prone to voicing is unclear. Másdóttir (2019) observes that Icelandic WI voiceless nasals are low in type frequency, which can contribute to later mastery (e.g., Vihman et al., 1994; Ingram, 1999); especially combined with the fact that voiced nasals are high in type frequency (and so are likely outputs). Further, there are few minimal pairs with voiced nasals, leading to low functional load, also potentially contributing to later acquisition (e.g., Stokes & Surendran, 2005). Voiceless nasals may have lower acoustic salience than voiceless liquids (which may sound more fricative-like), but there are aspects of the data (e.g., substitution of pre-aspirated stops in voiceless-nasal-stop clusters) that show that children have likely perceived the [+s.g.] feature. The skewing towards [-s.g.] is reminiscent of patterns for post-aspirated stops (also [-continuant]), which are also subject to [-s.g.] outputs, suggesting an acquisition pattern shared between similar speech sounds, but with voiceless nasals delayed more than post-aspirated stops. Bombien (2006) reports that Icelandic [n̥] can be produced with breathy voice, a more complex articulation that is both [+s.g.] and [+voice]; this added complexity may influence the late acquisition of the voiceless nasals, both because the increased similarity to voiced nasals increases the competitiveness of voiced-nasal outputs, and because greater segmental complexity is often associated with later acquisition.

The difference between voiceless liquid and nasal sonorants is a clear instance where focus on full segmental match (voiceless nasals better than voiceless liquids) obscures differences in accuracy at the feature level (voiceless liquids better for [+s.g.] than voiceless nasals).

Clusters with voiceless fricatives and sonorants

By age three, [+s.g.] showed high match levels in clusters of a voiceless fricative or sonorant and a stop, equivalent to match levels for singleton targets. Where full segments mismatched, [h] often replaced the fricative or sonorant, resulting in a pre-aspirated stop.

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This substitution pattern potentially lends support to the perspective (see Introduction) that in such clusters (e.g., |θk|, |n̥t|), the stop is essentially pre-aspirated, but with its [+s.g.] feature superimposed on the fricative or sonorant. Voiceless nasal-stop clusters had fewer mismatches (and higher FSM) than liquid-stop clusters, possibly because [+nasal] was earlier-acquired than the manner features for the liquids. Mismatches for nasal-stop clusters were similar to those for liquid-stop clusters, although geminate [-s.g.] stops were more frequent for the nasal clusters, possibly showing a similarity effect, both stops and nasals being [-continuant]. Complex mismatches that preserved [+s.g.] in the first segment but migrated [+nasal] to the second (e.g., |n̥k| → [xn]), were rare but show the independent nature of features.

Other features

In terms of other features, certain segment types (post-aspirated stops, fricatives) were more subject to place changes than others (sonorants), e.g., showing "Velar Fronting" or labial assimilation. Sometimes both manner and place changed, giving [h] as a possible output. If oral place or manner features are challenging for some reason, an option for output is a glottal articulation ([ʔ] or [h]). While [h] will then look like a purposeful match for [+s.g], this apparent match may be the serendipitous result of [h] being the only available output for an impossible segmental target. Similarly, if a certain place or manner is challenging, and therefore not produced, the [+s.g.] feature may be lost because of other constraints in the system, pushing outputs that are [+voiced] or [+constricted glottis]. Those constraints may not be on [+s.g.] as such but on other features with which [+s.g.] is correlated in some way.

Mismatches and features: summary

Overall, mismatches met expectations based on previous research, relative markedness, and feature theories. The least complex/marked [+s.g.] segment [h] was a frequent replacement for other more marked targets, with some similarity effects (implicational universals, Jakobson, 1968/1941) in terms of manner features, i.e., [+sonorant, +continuant] [h] replacing other [+sonorant] targets more than obstruents, and other [+continuant] targets more often than stops.

In nonlinear phonological accounts (e.g., Bernhardt & Stemberger, 1998; McCarthy, 1988), features are described as acting/developing independently but also as subject to interactions arising from dominance relationships within prosodic and feature hierarchies. Retention of [+s.g] in segmental mismatch patterns shows the development of [+s.g.] as an independent feature (generally early-acquired feature: Table 2).

As tokens showing full segmental match also match for [+s.g.], these data suggest that all segments with [+s.g.] benefit from the feature having a high type and token frequency.

The different segments reinforce learning of the feature, and each individual speech sound is not on its own for independent development. However, the loss of [+s.g.] in voiceless nasals and post-aspirated stops also shows interactions with manner features (difficulty of combining [+s.g.] and [-continuant]). Interactions were also observed in deletion of the target segment (and [+s.g.] along with it) and in maintenance of segment/syllable timing (e.g., gemination of consonants, use of pre-aspirated stops to replace clusters).

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Directions for future research

This data set was collected as a part of phonological assessment standardization and was not aimed specifically at addressing [+s.g.]. This resulted in different numbers of target words for different consonant types; e.g., we had more than four times as many tokens of WI fricatives as WI sonorants, and twice as many tokens of voiceless liquids as voiceless nasals. The large number of participants compensated for this, but a more focused study would strengthen the conclusions. Acoustic analysis, particularly of pre- and post-aspirated stops, might provide more detail on the development of [+s.g] in those categories. Finally, inclusion of data from younger children (1;0-2;5) would perhaps more clearly delineate the progressive development of [+s.g.] across the various categories.

Conclusions

It is relatively common to focus on the development of particular categories by manner (e.g., fricatives, liquids) or place (e.g., coronals, velars), and sometimes to examine the interaction of voicing with manner (e.g., voiced fricatives). It is less common to focus on all segments that share a particular feature, particularly one involving glottal aperture. We focused on [+s.g.] because it is so uniquely prevalent in Icelandic phonology. The feature [+s.g.] was generally mastered very early, suggesting that each speech sound that contains it benefits from the high frequency of the feature across all speech sounds in the language. This is consistent with theories such as those proposed by Bernhardt and Stemberger (1998), Beckman and Edwards (2010) and Namasivayam et al. (2020).

However, the data suggests that combining [+s.g.] with [-continuant] (stops and nasals) is more challenging than with [+continuant] (fricatives and liquids). Further, there were notable interactions with place and manner features and word structure context (syllable position, singleton/cluster), interactions that might have been missed without taking a feature-based approach. Few languages have such a diverse set of [+s.g.] segments, but one hopes that future studies will address phonological development in such languages. Research might also focus on languages that have an unusually ubiquitous feature, observing its independent development, and its interactions with other elements in the phonological system.

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/S0305000923000582.

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Appendix 1

Target words in the speech sample.

Words	Adult transcription	|h|	Post-asp. stops	Pre-asp. stops	Voicel. fricat.	Voicel. sonor.	English
húfa	ˈhuːva	WI h					beanie
hús	huːs	WI h			WF s		house
hundur	ˈhʏntʏr̥	WI h				WF r̥	dog
hægt	haixt	WI h					slowly
hár	hauːr̥	WI h				WF r̥	hair
hella	ˈhɛtla	WI h					pour
hestur	ˈhɛstʏr̥	WI h					horse
peli	ˈpʰɛːlɪ		WI pʰ				baby bottle
peysa	ˈpʰeiːsa		WI pʰ		WM s		sweater
tennur	ˈtʰɛnːʏr̥		WI tʰ				teeth
tígrisdýr	ˈtʰiːkrɪsˌtiːr̥		WI tʰ			WF r̥	tiger
kíkja	ˈcʰiːca		WI cʰ				peek
kona	ˈkʰɔːna		WI kʰ				woman
kaffi	ˈkʰafːɪ		WI kʰ		WM fː		coffee
kubbar	ˈkʰʏpːar̥		WI kʰ				blocks
kartafla	ˈkʰar̥tapla		WI kʰ			WM r̥t	potato
kanína	ˈkʰaːnina		WI kʰ				rabbit
þvottavél	ˈθvɔhtaˌvjɛːl̥			WM ht		WF l̥	washing machine
jakki	ˈjahcɪ			WM hc			jacket
dúkka	ˈtuhka			WM hk			doll
klukka	ˈkʰlʏhka			WM hk			clock
smekk/ur	ˈs(p)mɛhk/ʏr̥*			WM/WM hk			bib
epli	ˈɛhplɪ			WM hpl			apple
detta/datt	ˈtɛhta/taht*			WM/WF ht			fall/fell
fata	ˈfaːta				WI f		bucket
fíll	fitl̥				WI f		elephant
fiskur	ˈfɪskʏr̥				WI f		fish
fugl	fʏkl̥				WI f	WF kl̥	bird
fiðrildi	ˈfiðrɪltɪ				WI f		butterfly
sápa	ˈsauːpa				WI s		soap
sól	ˈsouːl̥				WI s	WF l̥	sun
sög	ˈsœːx				WI s, WF x		saw
sebrahestur	ˈsɛːpraˌhɛstʏr̥				WI s		zebra
sólgleraugu	ˈsouːlˌklɛːrøyɣʏ				WI s		sunglasses

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(Continued)

Words	Adult transcription	|h|	Post-asp. stops	Pre-asp. stops	Voicel. fricat.	Voicel. sonor.	English
hjarta	ˈçaˌrta				WI ç	WM ˌrt	heart
hjóla	ˈçouːla				WI ç		cycle (verb)
þumall**	ˈθʏːmatˌl				WI θ		thumb
gaffall	ˈkafːatˌl				WM fː		fork
lesa	ˈlɛːsa				WM s		read
blása	ˈplauːsa				WM s		blow
vasi	ˈvaːsɪ				WM s		pocket
risaeðla	ˈrɪːsaˌɛðla				WM s		dinosaur
nef	nɛːf				WF f		nose
voff	vɔfː				WF fː		woof
glas	klaːs				WF s		glass
mús	muːs				WF s		mouse
grís	kriːs				WF s		piglet
brauð	prøyːθ				WF θ		bread
snuð	s(t)nʏːθ				WF θ		pacifier/dummy
hnífur	ˈˌniːvʏˌr					WI ˌn	knife
hlaupa	ˈˌløyːpa					WI ˌl	run
hringur	ˈˌrɪŋkʏˌr					WI ˌr	ring
stelpa	ˈstɛˌlpa					WM ˌlp	girl
bolti	ˈpɔˌltɪ					WM ˌlt	ball
mjólka	ˈmjouˌlka					WM ˌlk	milk (verb)
lampi	ˈlamˌpɪ					WM mˌp	lamp
banka	ˈpauŋˌka					WM ŋˌk	knock
spil	spɪːˌl					WF ˌl	cards
þrír	θriːˌr					WF ˌl	three
tveir	tʰveiːˌr					WF ˌr	two
plástur	ˈpʰlaustʏˌr					WF ˌr	bandage
bíll	pitˌl					WF tˌl	car
útvarp	ˈuːtvaˌrp					WF ˌrp	radio

*/ˈs(p)mɛhkʏˌr/ (NOM.) or /s(p)mɛhk/ (ACC.); /ˈtɛhta/ (INF.) or /taht/ (PAST.3SG)

**alternatively *þumalfingur* or *þumalputti* (same word meaning), both with /ˈθʏːmal-/

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