Beiträge aus Forschung und Anwendung

Phonetik

An acoustic study of schwa syllables in monolingual and bilingual German-speaking children

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Abstract

There is little known on the acoustic characteristics of schwas in young children although schwa poses challenges for children in development and also in the acquisition of a second language. This study examines the acoustic correlates of schwa in German-speaking monolingual and bilingual children, aged 2;7 to 3;1. It provides acoustic data on different types of schwa syllables (schwa-only, R-colored schwa, syllabic consonants) in words of differing length (two-syllable vs. multisyllabic) and across different phrase positions (phrase-final vs. non-final), as well as examines whether bilingualism influences the production of schwa. Duration and formant frequency measures were conducted on over 700 productions of schwa syllables extracted from spontaneous speech recordings of three monolingual and three bilingual children. Results indicated significant effects of schwa-syllable type on duration and formant frequency measures as well as some differences due to phrase position. There were few differences pertaining to bilingualism with the exception of an increased rate of vowel epenthesis in the production of target syllabic consonants by the bilingual children. The discussion focuses on the acoustic challenge of acquiring schwa-only in comparison to other schwa syllables, which may relate to its reduced length and its variable formant frequency realization.

1 Introduction

Schwa is one of the most frequently occurring vowels in Germanic languages such as Dutch, English, and German (Delattre 1965). The linguistic literature is replete with descriptions of schwa due to its unique phonetic and phonological properties (Becker 1998; Féry 1995; Wiese 1988, 1996 for German; Flemming & Johnson 2007; Hammond 1997 for English; Kager 1989; Kager & Zonneveld 1986; van Oostendorp 1995, 2000 for Dutch). Phonetically, schwa is characterized by low amplitude, short duration, and centralized vowel quality.

Phonologically, schwa is said to be unspecified either prosodically or segmentally (Féry 1995; Kager 1989; van Oostendorp 1995). Despite the attention it has received in the adult phonological literature, schwa has been little studied in children. To date, there has been no comprehensive study of the acoustic correlates of schwa in young children. We believe such data are important since they may help to explain why schwa syllables, despite their high frequency, are difficult to acquire for some children (Kehoe & Lleó 2003; Levelt 2008).

The aim of this study is to provide acoustic data on schwa syllables in three-year-old German-speaking (monolingual and bilingual) children (aged 2;7 to 3;1). We consider three types of information which may shed light on schwa acquisition. First, we compare the acoustic qualities of different types of schwa syllables (schwa-only [ə], R-colored schwa [ɐ], and syllabic consonants [n̩, l̩]).[1] These three types of schwa syllables are united in phonological accounts such as the one of Féry (1995) in which they are all claimed to be non-moraic. This might suggest that they are all acquired at the same time. Research based on phonetic transcription, however, indicates that syllabic consonants and R-colored schwa are more easily acquired than schwa-only syllables (Kehoe & Lleó 2003). Kehoe and Lleó (2003) focused on phonological reasons for these differences whereas this study explores phonetic reasons as to why certain schwa syllables are easier to produce than others. Second, we examine the realizations of schwa in words of different length and across different phrase positions. This information will allow us to determine whether schwa is conditioned by the same prosodic dimensions in child as in adult speech. Finally, we compare the production of schwa syllables by monolingual and bilingual German-speaking children. Numerous studies indicate that second language and bilingual learners experience difficulty producing reduced or schwa syllables (Flege & Bohn 1989; Kondo 2000). Thus, analyzing them in a young bilingual population should provide additional information on the difficulties children face in acquiring schwa. Since the bilingual children speak another language (i.e., Spanish) that does not contain schwa, we posit that they may realize them with longer duration or with different vowel quality than do their monolingual counterparts.

In sum, the goal of the study is to provide information on the acquisition of schwa syllables by examining the acoustic characteristics of different types of schwa syllables, their realization in words of differing length and phrase position and the production of them by monolingual and bilingual speakers. In the remainder of the *Introduction*, we discuss themes which are relevant to the current study which include: schwa syllables in German, the acoustic correlates of schwa syllables, the acquisition of schwa, phonetic differences between schwa syllables, factors influencing schwa production, and the production of schwa by monolingual and bilingual speakers.

[1] Throughout the manuscript, we use the cover term "schwa syllables" to refer to all syllables containing a schwa variety; "schwa-only" to refer to syllables containing [ə] only, "R-colored schwa" to refer to syllables containing [ɐ], and "syllabic consonants" to refer to syllables containing [n̩, l̩] or [ən, əl].

1.1 Schwa syllables in German

Schwa is the most frequent vowel in German, being present in almost 30% of words (Kohler 1995, based on Kiel lexicon of 23985 words) and in 15% of vowels in connected speech (Pätzold & Simpson 1997, based on Kiel corpus of read speech). Its most typical occurrence is in the second syllable of disyllabic words: 82% of mono-morphemic disyllabic nouns in German have an initial stressed syllable and a final schwa syllable (Bartels, Darcy, & Höhle 2009).

Schwa in German can be separated into two categories: underlying and reduction schwa (van Oostendorp 1995, 1998, 2000). In the current study, we focus only on underlying schwa, that is, forms which will always be heard by the child as schwa. Underlying schwa syllables can be further divided into three categories: 1. schwa-only; 2. R-colored schwa; and 3. syllabic consonants as shown in (1a, b, c) respectively.

(1) Different types of schwa syllables

a.	Bien/ə/	Bien[ə]	"bee"
b.	Tig/ər/	Tig[ɐ]	"tiger"
c.	Ig/əl/	Ig[l̩]	"hedgehog"

R-colored schwa may be denoted underlyingly as schwa plus /r/ (i.e., /-ər/) but its phonetic realization is most commonly that of a monophthongal vowel of low central quality (e.g., [ɐ]).[2] Similarly, syllabic consonants may be underlying transcribed as schwa plus sonorant consonant (e.g., /-əl/, /-ən/); however, they are frequently realized as syllabic consonants. How frequently schwa plus consonant surfaces as syllabic consonant in German is dependent upon several factors, including the phonetic quality of the preceding context, speech rate, and the phonetic quality of the following sonorant consonant. Kohler and Rodgers (2001) report high rates of deletion of schwa in C + [ən] context with rates exceeding 90% when the preceding consonant is a plosive or a fricative.[3] Lower rates of schwa deletion have been reported by other investigators. Kasuya and Arai (2013) report that German native speakers delete schwa 83% of the time in fast speech, 52% of the time when speaking at a normal speech rate, and 11% of the time in slow speech. Gut (2003) found that native German speakers deleted schwa in read speech 60% of the time. Toft (2002), when studying syllabic consonants in English, found that /l/ was more frequently realized as syllabic than /n/, and, the syllabicity of /n/ was dependent on the place of articulation of the preceding consonant and on whether the /ən/ was preceded by a singleton consonant or a cluster. Based on the preceding discussion, we assume that children will hear [ə]

[2] Some German phoneticians also transcribe R-colored schwa as [ʌ] (Hall, 1992).

[3] Authors differ as to whether they consider syllabic consonants or schwa plus sonorant consonant as the default representation (Féry, 1995). Thus, the alternation of schwa plus sonorant consonant or syllabic consonant (e.g., [ən] or [n̩]) may be referred to as vowel deletion or as vowel epenthesis. We remain agnostic regarding the default representation of target syllabic consonants and use the terms "vowel deletion" and "vowel epenthesis" interchangeably to refer to the alternation of schwa plus sonorant consonant or syllabic consonant in the current article.

and [ɐ] for schwa-only and R-colored schwa respectively, but may be exposed to both syllabic consonants and schwa plus sonorant consonant variants for the third category of schwa.

1.2 Acoustic correlates of schwa

Syllables containing schwa are phonetically different from syllables containing full vowels (Low, Grabe, & Nolan 2001). We concentrate here on the duration and formant frequency characteristics of schwa. Koopman-van Beinum (1994) reports a mean duration of 47 ms for Dutch schwa in spontaneous speech similar to the value reported by Bürki, Fougeron, Gendrot, and Frauenfelder (2011) for French schwa (i.e., 51 ms) in radio broadcasted news. Zimmerer and Reetz (2011) present histograms of vowel duration suggesting that the most frequent duration of underlying schwa in German speech is in the vicinity of 30 to 50 ms. The shortness of schwa, although evident in non-phrase-final position, is not necessarily evident in phrase-final position where schwas may sometimes be as long as a non-final stressed vowel (Fischer-Jørgensen 1969). Flemming and Johnson (2007) document phrase-final schwas in English of 153 ms in comparison to non-final schwas of 64ms. Similarly, Marusso and Silva (2007) report relatively long mean durations for phrase-final schwas (in two-syllable words) in Brazilian Portuguese and British-English speaking adults, of 123 ms and 163 ms respectively.

Concerning vowel quality, Patzold and Simpson (1997) report a close quality for German schwa having an F1 somewhere in the region of /e:/. The values for schwa in a corpus of read speech by adult male speakers were 370 Hz and 1521 Hz for F1 and F2 respectively. According to Pätzold and Simpson (1997), the close quality of schwa arises from the fact that speakers need to make a functional distinction between schwa and [ɐ] (e.g., bitte ['bɪtə] vs. bitter ['bɪtɐ]). The formant frequencies measured for [ɐ] by Pätzold and Simpson (1997) were 503 Hz and 1372 Hz. Others report a more mid or open of mid characterization of schwa. In the Kiel corpus of spontaneous speech, Zimmerer and Reetz (2011) report formant frequency values for underlying schwa by adult German male speakers of 509 Hz and 1712 Hz for F1 and F2 respectively. The reason for the different formant frequency values between the two sets of studies is not clear although the different methodologies (read vs. spontaneous speech) may play a role.

Phonetic studies in English indicate the importance of distinguishing between two categories of schwa: final and medial schwa (Flemming 2009; Flemming & Johnson 2007). Word-final schwa in English has a mid central vowel quality with a relatively stable F2 (around 1770 Hz) and a less stable F1, which varies according to speaker and speech rate. In contrast, medial schwa is characterized by extreme variability of F2 and a relatively stable F1 (around 430 Hz). The variable F2 arises due to coarticulatory effects from neighboring consonants, which may be particularly evident in schwa (in contrast to full vowels) because of its reduced length (Flemming & Johnson 2007).

1.3 The acquisition of schwa syllables

There is very little research on the acquisition of schwa but the studies which exist suggest that children take some time to acquire schwa. This is surprising given its high frequency and the fact that it often functions as an epenthetic vowel, a finding consistent with it being an unmarked element (Levelt 2008). What is the evidence that schwa is difficult to acquire? First, target schwa syllables are more frequently deleted in children's multisyllabic productions than target full vowels. This has been found to be the case in English, Dutch, and French (Kehoe 1999/2000; Taelman 2004; Andreassen, 2013). Second, target schwa syllables are frequently substituted with full vowels at the early stages of acquisition (Kehoe & Lleó 2003; Levelt 2008). There are few studies, however, which have directly compared the error rates of target schwa versus full vowels making the evidence here less strong. The fact that vowel errors are low in child speech in general, whereas the production of schwa as full vowel has been noted by several authors (Allen & Hawkins 1980; Andreassen 2013; Kehoe & Lleó 2003; Levelt 2008) seems to suggest, however, that schwa is more subject to substitution errors than other vowels.

Several studies have looked at the acquisition of schwa within the theme of vowel reduction and rhythm. According to Allen and Hawkins (1980), learning the rhythm of a language involves learning to reduce or shorten unstressed syllables in "acceptable ways". Transcription studies vary regarding the age at which children are able to reduce syllables in "acceptable ways". Allen and Hawkins (1978) found that English-speaking children (aged 2;2–3;9) reduced target syllables only 50% of the time in function words and multisyllabic content words, whereas Kehoe (2002a) found higher rates of vowel reduction for German-speaking children. She found that two-year-old German-speaking children reduced vowels with a mean accuracy rate of 64% which increased to 92% at age 3;0. In short, there is no consensus on when children are able to reduce syllables but it appears to be around 3;0 years or later.

Levelt (2008), although not directly looking at the acquisition of schwa from the perspective of rhythm, explored whether children's difficulties with schwa were related to the phonetics of phrase-final lengthening. On reanalysing her earlier data (Levelt, 2000), she found that the main domain in which full vowel production of schwa occurred was in utterance final position. She showed that some of the full vowel productions of target schwa thought to occur in non-utterance-final position turned out to be actually in utterance-final position since children inserted a silent interval within a phrase in these cases. Levelt (2008) cites the work of Cambier-Langeveld, Nespor and van Heuven (1997) which shows that the vowel preceding an utterance-final schwa is often lengthened in adult speech because the schwa is too weak to carry the length required by the utterance-final boundary. In contrast, the vowel preceding an utterance-final full vowel is not lengthened. Levelt (2008) conducted acoustic analyses of Dutch children's productions of two-syllable words containing utterance-final schwas and full vowels, and observed that there were no significant differences between the durations of full vowels preceding utterance-final schwas and full vowels. This suggested to Levelt (2008) that children have not yet learnt to transfer length from utterance-final schwa to the preceding syllable and, as a result, they strengthen schwa to full vowels. Lengthening of schwa is not an option due to a constraint against long schwas [*əː].

One potential problem with Levelt's (2008) account of schwa acquisition is that it focuses only on duration and not on vowel formant measures. Children's difficulty with schwa may be related to its vowel quality. Unfortunately, most large scale studies of vowel formants in children do not include the schwa vowel (McGowan, McGowan, Denny, & Nittrouer 2014; Vorperian & Kent 2007) so it is difficult to know whether schwa is subject to greater formant frequency variability than full vowels. Kehoe and Lleó's (2003) transcription study suggests that children have difficulty acquring the centralized vowel quality of schwa. They observed that prior to the acquisition of schwa, German-speaking children produced target schwa as a full vowel (most often as [ɛ]) and later as a vowel which could not yet be transcribed as a true schwa. At age 3;0, schwa-only syllables were transcribed 42% of the time as [ə] and 46% of time as [ɛ̈]. In contrast, target syllabic consonants were transcribed 95% of the time as syllabic consonants, suggesting that syllabic consonants may be articulatorily easier than schwa vowels. Kehoe and Lleó (2003) also did not find that R-colored schwa posed many difficulties for children in acquisition (see footnote 13). It was originally produced as full-vowel [a] and later as [ɐ]. One reason why schwa-only vowels pose greater difficulty than R-colored schwas and syllabic consonants may be due to the centralized vowel quality of schwa which lacks PoA specifications.

In sum, our knowledge of schwa acquisition is limited but the overall findings suggest that schwa takes a longer time to be acquired than other vowels. Levelt (2008) proposes that children's difficulty with schwa pertains to durational effects: children are unable to transfer final lengthening to the penultimate syllable and as a result they augment schwa to a full vowel. Kehoe and Lleó (2003) propose that children have particular difficulty acquiring schwa-only syllables in comparison to R-colored schwa and syllabic consonants, possibly because they lack PoA specifications.

1.4 Phonetic differences in schwa syllables

In this section, we explore duration and formant frequency differences between schwa-only, R-colored schwa, and syllabic consonants which may explain the different acquisition rates observed by Kehoe & Lleó (2003). As mentioned above, all schwa syllables are short but there may be differences in duration amongst the three types of schwa syllables which have consequences for acquisition. Unfortunately, we do not know of any study which has directly compared the durations of different schwa syllables in child or adult speech. Due to intrinsic vowel duration effects, it could be supposed that R-colored schwa which has an open quality may be longer in duration than schwa-only syllables which have a more closed quality. In the case of target syllabic consonants, there are two sources of information which suggest that children will more frequently realize them with a vocalic element than is typical of adult speech. One source of information stems from research on the acquisition of schwa in French. The French schwa is somewhat analogous to the German syllabic consonant in that there exists two variants for many lexical forms: one with and one without schwa (e.g., [pti] or [pəti] for petit "small"). Andreassen (2013) observed that the presence of schwa in child speech was greater than in adult speech and that French-speaking children were more likely to realize the variant with schwa than the one without. If German acquisition of schwa is similar to French, the most frequent child form could also be the variant with schwa. Another source of information is the finding that schwa alternation in German adult speech is influenced by speech rate (Kasuya and Arai 2013). Given that children's speech rate is slower than adults' (Chermak & Schneiderman 1986), their rate of schwa deletion may be akin to the lower rates observed in slow speech by adults (Kasuya & Arai 2013). Consequently, syllabic consonants may be longer in duration than schwa-only and R-colored schwas due to the presence of the vocalic element plus consonant.

One caveat to this statement is the fact that Kehoe and Lleó (2003) did not document a high proportion of [ə] + C variants. Children produced target syllabic consonants first as full vowel plus consonant (e.g., [ʔapɛl] for Apfel "apple") and later as syllabic consonants (e.g., [ʔapl̩]) without an intervening phase of schwa + consonant (e.g., [ʔapəl]). However, their study was based on phonetic transcription and an acoustic analysis may yield a higher rate of schwa production than previously documented. Nevertheless, there could be articulatory reasons why syllabic consonants are early acquired. Pouplier and Beňuš (2011) investigated the articula-tory dynamics of syllabic consonants in Slovak. They found, on the basis of kinematic measures, that a consonant did not become more vowel-like when occupying the syllable nucleus position but in terms of articulatory timing, a syllabic consonant was subject to less overlapping articulatory gestures than a vocalic syllable. Since overlapping articulatory gestures pose difficulty for developing learners (McAllister Byun 2011), children may favor a syllabic consonant rather than a short vocalic nucleus plus consonant.

In sum, we expect duration differences between the three types of schwa syllables, with schwa-only syllables being the shortest in length and R-colored schwa and target syllabic consonants, when realized as vowel + consonant, being the longest. We do not know whether target syllabic consonants, when realized as syllabic consonants, are longer or shorter than vocalic schwa syllables. If significant duration differences are discovered between the three types of schwa syllables, this may explain the different acquisition patterns documented by Kehoe and Lleó (2003). Shorter segments may be more difficult to acquire than longer segments because they lead to a more complex rhythmic pattern when produced in running speech (i.e., stress-timed pattern).

Turning to vowel formant information, we have reviewed studies which document clear quality differences between the two types of vocalic schwa ([ə], [ɐ]) in German adult speech (Pätzold & Simpson 1997); however we do not know whether children also distinguish reduced vowels such as [ə] and [ɐ] in terms of their formant structure. In adult speech, schwa is reported to be not completely "targetless" but to have a weak mid-central specification. This is indicated by studies which show that the formant values for schwa deviate from the interpolated trajectory for the preceding and the following vowels (Barry 1998; Browman & Goldstein 1992; Flemming 2009). Even given this mid-central specification, schwa is subject to a great deal of spectral variation due to co-articulatory effects from surrounding consonants. This may impact on acquisition in two ways. Schwa may be difficult to acquire from a perceptual point of view. Children may take time to define the vowel space which is acceptable for target schwa. From a productive point of view, schwa poses a speech motor challenge since children need to gain control over co-articulation. Studies differ as to whether children show more co-articulation than adults (Nittrouer & Whalen 1989; Nittrouer, Neely, & Studdert-Kennedy 1996), less co-articulation (Green, Moore, & Reilly 2002) or similar degrees (Sereno, Baum, Marean, & Lieberman 1987) but they all indicate that children display greater articulatory variability than adults (Goffman, Smith, Heisler, & Ho 2008; Zharkova, Hewlett, & Hardcastle 2011). This may manifest as high formant frequency variability in acoustic measures. We posit that R-colored schwa may be less subject to formant variability due to its more distinct (open) vowel quality.

In conclusion, there are indications in the phonetic literature that not all schwa syllables are equal. Children may experience the greatest difficulty acquiring schwa-only syllables in comparison to R-colored schwa and syllabic consonants because of their shorter duration and more variable formant structure.

1.5 Factors influencing schwa production

Studies in adult speech indicate that several factors influence the length of vowels including word length and phrase position. Vowels are longer in shorter than longer words (Lehiste 1972; Port 1981). Lehiste (1972) showed that the length of the syllable nucleus in single words such as <u>stick</u> or <u>sleep</u> decreased in length when morpheme endings were added (e.g., <u>stickiness</u>, <u>sleepiness</u>) or when the words were embedded in short phrases (e.g., <u>the stick fell</u>, <u>sleep heals</u>).

Vowels are longer in phrase-final than in non-final position (Crystal & House 1988; Klatt 1975; Lindblom 1978). Studies have also established a positive relationship between the depth of the prosodic boundary and degree of segment lengthening with utterance-final position engendering the greatest degree of lengthening and other prosodic positions such as phonological phrase and prosodic word engendering less lengthening (Cambier-Langeveld et al. 1997).

Prosodic position may also be important when vowel formants are considered. As discussed previously, Flemming (2009) has reported that the formant values of schwa syllables in English may vary considerably depending upon whether they are word-final or -medial. In particular, the F2 of medial schwa may be extremely variable due to coarticulatory effects from neighboring consonants.

In this study, schwa will be measured in words of different length and in words occuring in different phrase positions; therefore, it is important to examine the influence of word length and prosodic position on the acoustic qualities of schwa. We are interested in determining whether schwa is conditioned by the same prosodic dimensions in child as in adult speech. Another reason to compare schwa production in utterance-final and non-final position is to test Levelt's (2008) proposal that children's difficulty with schwa pertains mainly to utterance final position. We expect to see vowel quality differences between utterance-final and non-final schwa indicative of full vowel augmentation in final position only. We do not expect to see durational differences between the two utterance positions because of the constraint [*əː] which prevents children from realizing long schwas.

1.6 The production of schwa by monolingual and bilingual speakers

Many studies show that second language learners experience difficulties reducing or not reducing vowels to an appropriate extent (Bond & Fokes 1985; Flege & Bohn 1989; Kondo 2000). For example, Kondo (2000) found that Japanese speakers of English were more likely to produce longer schwas in English than native speakers and to produce vowels with formant values more similar to the Japanese vowel /a/ than to the English schwa. Gut (2003) found that Chinese, Polish, and Italian speakers of German produced significantly lower stress-to-unstress duration ratios (approximately 1.5) than native German-speakers (1.9), indicating that they were not reducing vowels sufficiently to produce acceptable sounding schwas. Kasuya and Arai (2013) found that Japanese elementary speakers of German frequently produced schwa as a full vowel with [e, ɛ] quality. They also produced vowels of longer duration than native speakers and Japanese advanced speakers, and they never deleted vowels, which should have been the case since the target schwa syllables could also be realized as syllabic consonants. Indeed, although Japanese advanced speakers of German approximated the native speakers of German in the acoustic characteristics of schwa, they rarely realized syllabic consonants in contrast to the native speakers who did (deletion of schwa in fast speech: native: 83%; advanced learners: 26%; elementary learners: 0%). Similarly, Gut (2003) found that native German speakers deleted schwa more than 60% of the time in words ending in /Cən/ or /Cəm/ but Italian and Polish speakers of German did so to a lesser degree (approximately 40 to 50%) and Chinese speakers of German rarely deleted schwa (approximately 20%). In sum, findings on the production of schwa syllables by second-language learners of German suggest that they are not only likely to produce schwa with different acoustic qualities to native German speakers, but they are also less likely to realize syllabic consonants than native speakers.

The studies reported above were on second language learners, that is, speakers who have acquired their second language after childhood. Byers and Yavas (2016) found that age of L2 acquisition was a predictive factor in determining how native-like schwa production was. They found very few differences between adult monolinguals and early Spanish-English bilingual adults (i.e., bilinguals who had acquired English before the age of 10 years) in the duration of deletable and nondeletable schwa in English. This was in contrast to the findings of schwa production in a group of late Spanish-English bilinguals (i.e., bilinguals who had acquired English after the age of 10 years), who displayed significantly longer schwas than monolinguals and early bilinguals. Similarly, Kehoe and Lleó (2017), while finding some small differences in the $\text{ratios}_{\text{stress/unstress}}$ between young German monolinguals and bilinguals, found many non-significant differences in schwa duration between the two groups, suggesting that schwa production was not overly affected in young simultaneous bilinguals.

In sum, studies indicate that second-language and bilingual learners experience difficulty acquiring schwa syllables, although the evidence is less strong in the case of bilinguals who have acquired their second language at an early age. They may acquire schwa syllables similarly to monolinguals.

1.7 Predictions of study

This study examines the acoustic correlates (duration and formant frequencies) of schwa syllables in German-speaking monolingual and bilingual children. We test children in the age range 2;7 to 3;1 since previous studies indicate that, by this age, German-speaking children realize segments that can be perceptually identified as schwa, central vowels or syllabic consonants most of the time (Kehoe & Lleó 2003).

We consider three sources of information on the acquisition of schwa. First, we examine the acoustic characteristics of different types of schwa syllables: schwa-only, R-colored schwa, and syllabic consonants. Based on the evidence presented above, we expect that children will produce schwa-only syllables with shorter duration than R-colored schwa and syllabic consonants. We do not know, however, whether they will distinguish schwa and R-colored schwa in terms of formant frequency values. We predict, nevertheless, that children will display greater formant frequency variability for schwa-only compared to R-colored schwa. In terms of the realization of syllabic consonants, we predict that children will more frequently realize them with a vocalic element than is typical of adult speech. This prediction is based on findings of schwa acquisition in French (Andreassen 2013) and on the fact that children use a slower speech rate than adults (Kasuya & Arai 2013). Alternatively, children may realize target syllabic consonants as syllabic consonants with rates similar to those of adults because they are articulatory easy gestures (Pouplier & Beňuš 2011).

Second, we examine schwa in words of different length (two-syllable versus multisyllabic words) and in different phrase positions (utterance-final versus -non-final position). We predict that if children have developed adult-like control over schwa syllables, they will produce longer schwas in shorter versus longer words and in phrase-final versus non-final position as has been observed in phonetic studies of adult speech (Crystal & House 1988; Klatt 1975; Lehiste 1972; Lindblom 1978). Alternatively, if children are still in the process of acquiring schwa, we may observe phonetic effects akin to those predicted by Levelt (2008) in which children display vowel quality differences between utterance-final and non-final position but not vowel quantity differences.[4]

Finally, we compare realization of schwa by monolingual versus bilingual speakers. Since the bilinguals are also speaking a language which is characterized by the absence of schwa syllables, we predict that the production of schwa syllables may pose difficulties for them. The most likely scenario is that they will produce schwas with longer duration and less central vowel quality, realizing them more like full vowels than their monolingual counterparts. In addition, they may realize target syllabic consonants more frequently with a schwa plus consonant sequence than as a true syllabic consonant as has been found for second language learners of German (Gut 2003; Kasuya & Arai 2013). Alternatively, they may display few differences in the acoustic characteristics of schwa in comparison to monolingual speakers as has been documented for early bilingual speakers (Byers & Yavas 2016; Kehoe & Lleó 2017).

2 Method

2.1 Participants

The participants in this study include three monolingual German (Britta, Marion, and Thomas) and three bilingual German-Spanish children (Simon, Jens, and

[4] A more direct test of Levelt's (2008) proposal would have been to examine whether children transfer length to the full vowel preceding utterance-final schwa syllables but not before utterance-final full vowels. The reduced numbers of words containing utterance-final full vowels in the database prevented this type of analysis.

Manuel) growing up in Hamburg, Germany.[5] All children, monolingual and bilingual, were from middle-class educated families. All parents (mothers and fathers) had graduated from high school and had done university or tertiary-level studies.

The bilingual children were children of Spanish-speaking mothers and German-speaking fathers, whereby each parent followed the 'une personne, une langue' rule by addressing the child in his/her respective language. The parents' language of communication was primarily German in the case of Jens and Manuel, and both Spanish and German in the case of Simon. Analyses based on Mean Length of Utterance (MLU) and percentage of utterances corresponding to the target language within a recording session indicated that the three children were balanced bilinguals (Kehoe, Lleó & Rakow 2004).

2.2 Procedure

The children, monolingual and bilingual, were recorded longitudinally (on a fortnightly basis) from the onset of first words through to approximately three and a half years (see Lleó 2012, for a more detailed description of the corpus). They were audio-recorded in their homes in unstructured play sessions, while interacting with a parent and an experimenter. The bilingual children were visited by two separate teams: a German- and a Spanish-speaking team. If one of the parents were present, he/she had to be a native speaker of the language in which the recording was taking place. Only German words spoken in German sessions were included in the study. The monolingual children were recorded using a high fidelity cassette recorder (Sony TC-D_{10} PRO) and directional microphone (Beyer dynamic). The bilingual children were recorded using a mini-disc recorder (Sony MZ-R55CH) and directional microphone (Sony ECMT S120). In both monolingual and bilingual testing situations, the microphone was concealed in a vest worn by the child. Following testing, all sessions were glossed and phonetically transcribed by native German speakers.

2.3 Stimuli

For the purposes of the current study, all target words containing underlying schwa were extracted from the data-base at age range 2;7 to 3;1 years. A list of the most frequent target words analysed in the study are given in Appendix A. Target words were divided into two groups based on the number of syllables in the target word: 1. Two-syllables (e.g., Katz[ə], Kat[ɐ], or Ent[n̩]); and 2.

[5] It should be pointed out that the children's recordings are quite old. The monolingual children were recorded in the 1990s and the bilingual children around 1999–2004. We do not believe that the age of the recordings bears on the findings. That is, we know of no research which indicates that the phonetic qualities of schwa have changed in the last 20–30 years.

Multisyllables whereby the number of target syllables could be three (e.g., geschlaf[n̩], Feu[ɐ]wehr, Steinpilz[ə]), four (e.g., Halt[ə]stell[ə], Bohrmaschin[ə], Kind[ɐ]wag[n̩]) or five (e.g., Loko-motiv[ə], runt[ɐ]g[ə]fall[n̩]). Target words were further divided into two groups based on phrase position: phrase-final and -non-final.[6] To be considered final, a target word had to be produced with non-suspensive intonation, and could not be followed by some other word within the same phonological phrase. An example of the different prosodic environments is presented in (2). The phrase-non-final condition also included schwa in word-initial position, as in the <ge> context.[7]

(2) Schwa in two-syllable vs. multisyllabic words and in different phrase positions

a.	two-syllable phrase-final	kleine Katz**[ə]**]$_{\text{phrase-final}}$
b.	two-syllable non-final	klein**[ə]** Katze]$_{\text{phrase-final}}$
c.	multi-syllable phrase-final	Badewann**[ə]**]$_{\text{phrase-final}}$
d.	multi-syllable non-final	Bad**[ə]**wanne]$_{\text{phrase-final}}$ or g**[ə]**schrieben]$_{\text{phrase-final}}$

Appendix B presents the numbers of schwa syllables analyzed across prosodic condition. The aim was to achieve approximately 10 to 20 words in each prosodic condition for each schwa type (i.e., two-syllable final, two-syllable non-final, multi-syllable final, multi-syllable non-final for the categories: schwa-only, R-colored and syllabic consonant; in total 10–20 X 4 X 3 or 120 to 240 words per child);[8] however, this number was not obtained due to sampling gaps in the data-base. As can be seen, words containing R-colored schwa were less plentiful in the data-base than words containing schwa-only or syllabic consonants, and, across all conditions, multi-syllabic words containing schwa were less frequent than two-syllables words containing schwa. The total number of schwa syllables analyzed was 733. The average number of schwa syllables analyzed per child were: schwa only = 51; R-colored = 28; and syllabic consonants = 43.

[6] In actual fact, "phrase-final position" refers to "utterance-final" position but we use "phrase-final" for convenience. Non-final refers to any situation in which the schwa syllable was not in utterance final position. Thus, the condition "multi-syllable phrase-non-final" could refer to the situation in which the multisyllabic word itself was utterance-final (e.g., Bad**[ə]**wanne]$_{\text{phrase-final}}$ or non-final (e.g., Bad**[ə]**wanne XX]$_{\text{phrase-final}}$. We do not make these finer distinctions to avoid having small group numbers.

[7] Preliminary analyses distinguished between word-medial and word-initial schwa but since there was no significant difference between these two groups, these conditions were collapsed.

[8] On some occasions, there was ambiguity as to whether the child intended to produce a schwa-only or a R-colored schwa in morphologically complex words. For example, the target form "ein dick[ɐ] Käfer" could have been produced as "ein dick[ə] Käfer" because the child had not acquired the morphological alternation rather than because of phonetic factors. In such cases, we relied on the phonetic transcription provided by the native transcribers. In ambiguous situations, the form was excluded.

2.4 Acoustic measures

The selected target words were segmented into stressed and schwa syllables using PRAAT (Boersma and Weenink, 2007). The segmentation of syllable boundaries was determined by examination of the time wave-form and spectrogram. Clear periodicity in the waveform, and onsets and offsets of the second formant were used to define the boundaries of the vowels. The extraction of duration and formant values (F1 and F2) for schwa syllables was initially carried out with the help of a PRAAT script.[9] Preliminary analyses indicated, however, that it was necessary to alter the default parameters of PRAAT on a vowel to vowel basis in order to achieve valid vowel measures for the child data (Derdemezis, Vorperian, Kent, Fourakis, Reinicke, & Bolt 2016). Thus, the formant values were re-measured manually by placing the mouse cursor at the mid-point of the vowel and by using the "Get Formant" command to retrieve F1 and F2 values. The parameters which allowed the most accurate tracking of vowel formants was number of formants =4 and maximum formant = 5500 through to 8000 Hz. According to Derdemezis et al. (2016), changing the number of formants from the default setting of 5 to 4 is equivalent to changing the number of LPC coefficients from 10 to 8, and this setting may be more appropriate for child speech. Vowel formants which were difficult to determine using spectographic display were also checked via spectral analyses Fast Fourier Transform (FFT) or Linear Prediction Coding (LPC). Vowel productions which were characterized by exceptionally high F_0 were excluded from the analyses because they resulted in artifically high formants. Other reasons for excluding tokens included whispered speech, noise ovelay, and extreme nasality.

In addition to the raw duration and formant values, we calculated normalized measures of duration ($ratio_{stress/unstress}$) and formant frequency.[10] In the case of duration, the ratio of the duration of the stressed and schwa syllable was determined. The stressed syllable was the preceding adjacent stressed syllable within the trochaic foot (e.g., "flie" in fliegen [ˈfliːgn̩] "to fly"). The only exception to this was initial "ge" forms, in which the adjacent stressed syllable following the schwa syllable was used (e.g., "schrie" in geschrieben). The duration of the entire rhyme of the stressed syllable was measured, which could include a long vowel (e.g., [iː] as in fliegen ['fliːgn̩] "to fly"), diphthong (e.g., [aʊ] as in Mause ['maʊzə]"mouse"), or short vowel plus sonorant coda (e.g., [ɛn] as in Ende ['ɛndə] "end"). The $ratio_{stress/unstress}$ allows the duration measures to be standardized in terms of speech rate. A ratio greater than 1.0 reflects a SW (strong weak) pattern in which the stressed syllable has increased duration with respect

[9] Formant values in this study differ from those reported in Kehoe and Lleó (2017) due to differences in methodology. Kehoe and Lleó (2017) derived formant values on the basis of a Praat script set to default parameters. In the current study, formants were measured manually and formant analyses parameters were varied on a vowel to vowel basis to achieve optimal formant tracking.

[10] We also calculated another normalized duration measure, $PVI_{duration}$ (see Ballard, Djaja, Arciuli, James, & van Doorn, 2012), but since it yielded similar results to $ratio_{stress/unstress}$, we present the ratio measures only.

to the schwa syllable. A ratio less than 1.0 reflects a WS (weak strong) pattern in which the schwa syllable has increased duration with respect to the stressed syllable. Gut (2003) reported $ratios_{stress/unstress}$ for adult German speakers of 1.9 but lower values for German as second language speakers.

To adjust for individual differences due to vocal tract size, raw F1 and F2 were normalized using a procedure outlined by Watt and Fabricius (2002) (see Barlow, 2014, for application of this procedure to bilingual data). It involved measuring the formant values of stressed vowels /a/ and /i/ for each child, estimating the value for /u/, and then determining the grand mean of these three vowels which served as the centroid (center of gravity) value S. All the observed formant values per child were divided by the S value yielding a ratio either below or above 1.0. The normalization was made separately for F1 and F2. The formant measures for vowels /a/ and /i/ were taken from the stressed syllables of words containing schwa syllables (e.g., /a/: Malen, Hase, Strasse; /i/: Biene, Fliege, Liebe). The formants were measured in a similar way to those of schwa syllables and were based on an average of 8 different stressed vowel productions per child. In addition to measuring the formant values of stressed vowels /a/ and /i/, we measured the formant values of stressed /ɛ/ (e.g., Schnecke, Trekker) and /ɪ/ (e.g., Fische, dicker) to serve as reference vowels in the descriptive analyses of vowel formants. The formants for /ɛ/ were based on an average of 10 stressed vowel productions per child and those for /ɪ/ on an average of 7 productions.

In the case of target syllabic consonants, we present duration but not formant frequency measures. Formants were extremely difficult to measure for target syllabic /n/ due to the presence of nasal formants (Toft, 2002). They were able to be measured for target syllabic /l/ but there were fewer target words with syllabic /l/ (syllabic /l/: n=65; syllabic /n/: n=195) making the statistical analysis of them less meaningful. We do investigate, however, the number of times target syllabic consonants were produced as syllabic consonant or vowel plus consonant. The presence of a vowel was determined by clear formant structure and a high amplitude waveform. It was often possible to see a clear distinction between the vowel and consonant in the time waveform (as in the production of machen spoken by Simon in Figure 1). The presence of a low amplitude waveform and indistinct formant structure (particularly F2 and higher formants) was typical of the acoustic profile of syllabic consonants (as in the production of binden spoken by Marion in Figure 2).

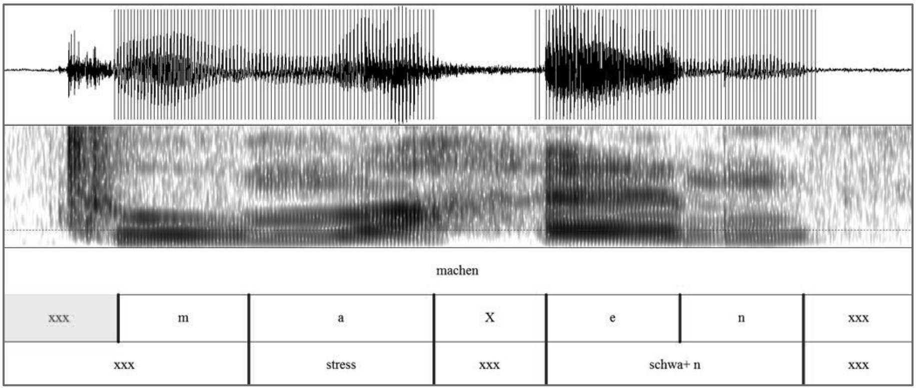

Figure 1: Time waveform, spectrogram and text grid display of the two-syllable word machen by bilingual child Simon illustrating the realization of vowel plus consonant for syllabic /n/.

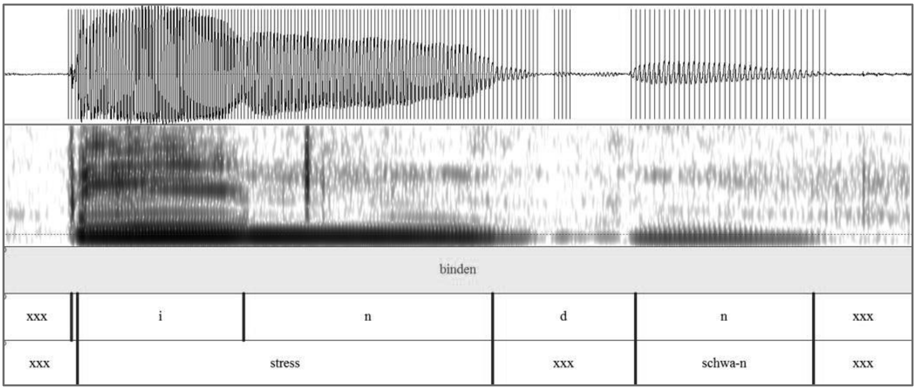

Figure 2: Time waveform, spectrogram and text grid display of the two-syllable word binden by monolingual child Marion illustrating the realization of syllabic consonant for syllabic /n/.

2.5 Reliability

A subset of productions (n=50 syllables) was reanalyzed by a second tester with a focus on verifying duration measures. The subset included productions of different types of schwa syllables from two different children. Inter-rater reliability was high based on a Pearson correlation coefficient ($r(47)=.920$, $p<.05$). The mean duration difference between the two sets of measures was 2.9 ms. An additional subset of productions (n=55 syllables) was reanalyzed by the original tester with the focus on verifying formant values. Again the subset included productions of different schwa syllables from two different children. Intra-rater reliability was high both for F1 ($r(53)=.995$, $p<.05$) and F2 ($r(53)=.994$, $p<.05$). The mean formant difference for F1 was 14 Hz and for F2 was 25 Hz.

2.6 Statistical analyses

The statistical analyses were performed using R statistical software (R Development Core Team 2015) and the lme4 package (Bates, Maechler, Bolker, & Walker 2014) for mixed effects models. To evaluate the contribution of each predictor in the model, we performed pairwise model comparisons between a saturated model and a more restricted model. The saturated model included all main effects and interactions. The more restricted model omitted the predictor under consideration. Comparisons were made using likelihood ratio tests (LRT) which yielded a chi-squared statistic. Fixed effects included schwa syllable type (schwa only, R-colored schwa, syllabic consonant), word length (two-syllable vs. multi-syllabic), phrase position (final, non-final), bilingual status (monolingual vs. bilingual), and phonological vowel length of the stressed syllable (short or long). The latter variable was included only for the normalized measure of duration since it would be influenced by the phonological length of the stressed syllable. A stressed syllable was coded as long when it included a long vowel, diphthong or short vowel plus consonant. The random part of the model included random intercepts for participants and items. Our dependent measures included two duration measures: raw duration, $\text{ratio}_{\text{stress/unstress}}$, and four formant frequency measures: raw F1, raw F2, normalized F1 and normalized F2.

3 Results

3.1 Duration

In the following presentation of the results, we first discuss the descriptive findings and then the outcomes of our statistical models. Tables 1 to 4 present the means and standard deviations of the raw duration and ratio measures according to the main factors examined. For findings on the duration values of different schwa syllables according to word length and phrase position, see Appendices C and D.

The mean duration of schwa syllables across all children and across all conditions was 160 ms. Figure 3 presents a histogram of schwa syllable duration. Most of the time, children produced schwas of 100 to 150 ms but a small proportion of the time, children produced schwas of less than 50 ms or greater than 350 ms.

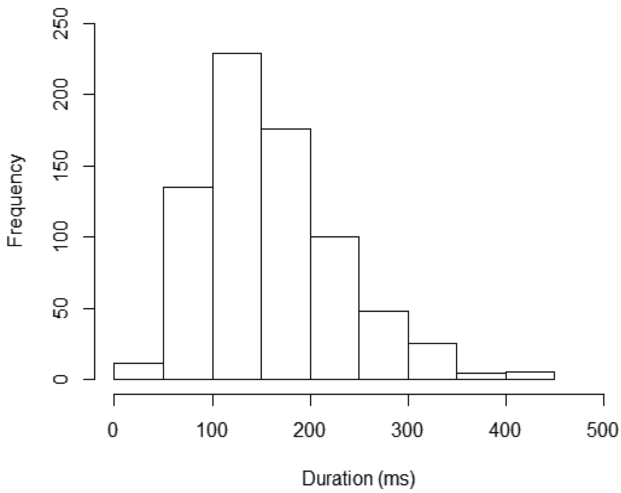

Figure 3: Histogram of schwa syllable duration.

Table 1 shows the duration findings for different schwa syllables. Children produced schwa-only syllables with shorter duration than R-colored schwas which in turn were produced with shorter duration than syllables with syllabic consonants. The normalized duration measures indicated higher stress-to-unstress ratios for schwa-only syllables in comparison to the other schwa syllables. In fact, the $\text{ratio}_{\text{stress/unstress}}$ was close to 1.0 for syllabic consonants meaning that stressed and unstressed syllables were similar in length for these types of schwa syllables.

	Schwa only[a]		**R-colored schwa**[b]		**Syllabic Consonants**[c]	
	Mean	sd	Mean	sd	Mean	sd
raw length	137.60	65.10	149.30	56.19	192.52	73.14
$\text{ratio}_{\text{stress/unstress}}$	1.62	1.03	1.34	0.70	1.12	0.55

a. The number of schwa syllables was 307.
b. The number of R-colored schwa was 167.
c. The number of syllabic consonants was 259.

Table 1: Means and standard deviations of raw and normalized duration measures for the three types of schwa syllables across all children.

Tables 2 and 3 present the duration measures according to whether schwa syllables appeared in in two-syllable versus multisyllabic words and in phrase-final versus non-final position. On average, schwa syllables were 10 ms longer when they were produced in shorter versus longer words and 50 ms longer when they appeared in phrase-final versus non-final position. The $ratios_{stress/unstress}$ were smaller in two-syllable words and in phrase-final position in comparison to the same normalized measures in longer words and in non-final position.

	Two-syllable[a]		**Multisyllabic**[b]	
	Mean	sd	Mean	sd
raw length	162.64	71.80	153.61	67.82
$ratio_{stress/unstress}$	1.35	0.82	1.44	0.88

a. The number of two-syllable words was 492.
b. The number of multisyllabic words was 241.

Table 2: Means and standard deviations of raw and normalized duration measures for schwa syllables in two-syllable and in multisyllabic words.

	Phrase-final[a]		**Non-final**[b]	
	Mean	sd	Mean	sd
raw length	178.37	72.73	131.90	57.02
$ratio_{stress/unstress}$	1.31	0.74	1.49	0.97

a. The number of phrase-final words was 438.
b. The number of non-final words was 295.

Table 3: Means and standard deviations of raw and normalized duration measures for schwa syllables in final and in non-final position.

Table 4 shows schwa duration values for monolingual and bilingual children. The mean schwa durations were very similar between the monolingual and bilingual children (i.e., approximately 160 ms) but the normalized values were slightly less for the bilingual children suggesting that they marked the difference between stress and unstress in a less extreme manner than the monolingual children.

	Monolingual[a]		**Bilingual**[b]	
	Mean	sd	Mean	sd
raw length	161.43	74.75	157.75	65.84
$ratio_{stress/unstress}$	1.43	0.87	1.33	0.81

a. The number of tokens for the monolingual children was 382.
b. The number of tokens for the bilingual children was 351.

Table 4: Means and standard deviations of raw and normalized duration measures of all schwa syllables for the monolingual and bilingual children.

We conducted a linear mixed effects model to determine what factors accounted for the raw duration measures. We entered as fixed effects schwa syllable type, word length, phrase position, and bilingual status. As mentioned, the random part of the model included random intercepts for participants and items. There were 733 individual raw duration measures. Results indicated that two main effects significantly improved model fit to data: schwa syllable type ($\chi^2(2)=62.91$, $p<.001$) and phrase position ($\beta=-38.21$, s.e.=5.05, $\chi^2(1)=55.80$, $p<.001$). Schwa syllables were not of equal length and phrase-final schwa syllables were longer than non-final schwa syllables. Multiple comparisons (Tukey) were carried out to determine which syllable types differed significantly from each other. These tests revealed that syllabic consonants were longer than schwa-only syllables ($z=8.11$, $p<.001$) and R-colored schwa ($z=5.30$, $p=<.001$); schwa-only and R-colored schwas were similar in duration ($z=1.66$, $p=.22$). No other predictor variable was significant. That is, schwas in two-syllable words were not significantly longer than schwas in multisyllabic words ($\beta=-9.31$, s.e.=5.70, $\chi^2=2.42$, $p=.11$) nor were the schwas produced by bilinguals significantly longer (or shorter) than the schwas produced by monolinguals ($\beta=-4.51$, s.e.=8.55, $\chi^2=.36$, $p=.55$).

In the next set of analyses, we conducted linear mixed effects models on the $ratios_{stress/unstress}$ to determine what factors accounted for the findings. In addition to the fixed effects mentioned above, we added the variable phonological vowel length to control for the fact that the stressed syllable adjacent to the schwa syllable could be phonologically long or short. Our results indicated that schwa syllable type significantly improved model fit ($\chi^2(2)=42.75$, $p<.001$). Multiple comparisons (Tukey) revealed that the stress-to-unstress ratios of all syllable types were significantly different. The ratio of stressed syllable to syllabic consonants was significantly smaller than the ratio of stressed syllable to schwa only syllables ($z=-6.60$, $p<.001$) as well as the ratio of stressed syllable to R-colored schwa ($z=2.73$, $p<.05$). In addition, the ratio of stressed syllable to schwa only syllables was significantly greater than the ratio of stressed syllable to R-colored schwa ($z=-2.93$, $p<.01$).

Phrase position as a factor did not make a significant contribution to model fit ($ratio_{stress/unstress}$: $\beta=-.07$, se.=.06, $\chi^2(1)=1.38$, $p=.24$). However, the interaction of phrase position and syllable type did ($\chi^2(2)=13.66$, $p<.01$). Multiple comparisons (Tukey) revealed that the ratios for schwa-only syllables were significantly greater in non-final in comparison to phrase-final position (1.8 vs. 1.4; $z=3.53$, $p<.01$) whereas the ratios for R-colored schwa (1.3 vs. 1.4; $z=-.68$, $p=.98$) and syllabic consonants did not differ according to phrase position (1.0 vs 1.2; $z=-1.25$, $p=.81$). Word length (two-syllables versus multisyllables) made a marginally significant contribution to model fit ($\beta=-.14$, se.=.07, $\chi^2(1)=3.47$, $p=.06$).

The factor phonological vowel length made a significant contribution to the model. The ratios of phonologically long stressed syllables to schwa syllables were significantly higher than the ratios of phonologically short stressed syllables to schwa syllables (β=-.47, se.=.07, $\chi^2(1)$=43.35, p<.001). The actual ratios were 1.57 (sd=.88) for stressed long and 1.03 (sd=.64) for stressed short vowels. Previous studies have indicated delay in bilingual children's acquisition of vowel length (Kehoe 2002b) so we examined whether bilingual children realized the ratios for long and short vowels differently from monolinguals. Results revealed that the bilinguals' ratios were lower for target long vowels in comparison to the monolinguals' ($\text{ratio}_{\text{stresslong/unstress}}$: 1.47 vs 1.67), although not for target short vowels ($\text{ratio}_{\text{stresslong/unstress}}$: 1.04 vs 1.02). However, there was no significant interaction ($\chi^2(1)$=1.48, p=.22), suggesting that the ratios of bilinguals and monolinguals for short versus long vowels were essentially the same.

Finally, we found that bilingual status as a main effect did not make a significant improvement to model fit. That is, monolinguals did not differ from bilinguals in the normalized duration measures (β=-.14, s.e.=.09, $\chi^2(1)$=1.85, p=.17).

In sum, linear mixed effects models conducted on raw and normalized duration measures revealed that several factors contributed to model fit. Schwa syllable type was a highly significant factor in both the raw duration and normalized measures. Word length did not make a significant contribution to raw duration measures; however, it had a marginal effect for normalized measures. Position made a significant contribution to model fit for the raw duration measures, but not a significant one for the normalized measures. There was a significant syllable type by position interaction, however, meaning that phrase position had an effect on certain schwa syllables (i.e., schwa-only syllables). The phonological vowel length of the stressed syllable also had a significant influence on our normalized measures. Finally, our results indicated no effect of bilingualism on schwa syllable durations. The length of schwa syllables was almost identical across monolingual and bilingual children, and the normalized measures, which took into account the relationship between stressed and unstressed syllables, were not statistically different between the two groups.

3.2 Formant frequency

Table 5 presents the means and standard deviations of F1 and F2 for schwa-only and R-colored schwa. Some schwa-only and R-colored schwa productions included in the duration analysis were excluded from the formant frequency analysis due to unclear formant structure (schwa-only: n=7; R-colored: n=4). Children produced schwa-only syllables with lower F1s and higher F2s than R-colored schwa similar to the formant patterns of adult vowels. Schwa-only syllables were characterized by greater variability of F2 (as suggested by the larger standard deviations); R-colored schwa was characterized by greater variability of F1. Table 6 presents the means and standard deviations of vowel formants for the two types of schwa syllables according to phrase position. There were some slight differences of formant values across phrase position. Table 7 provides F1 and F2 values of schwa-only and R-colored schwa in the monolingual and bilingual children. The bilinguals tended to have higher F1 and F2 values in comparison to the monolinguals.

		F1		**F2**	
	n	Mean	sd	Mean	sd
Schwa-only	300	744	152	2248	430
R-colored schwa	163	1019	216	1971	279

Table 5: Means and standard deviations for vowel formants in schwa-only syllables and R-colored schwa

		F1		**F2**	
	n	Mean	sd	Mean	sd
Schwa-only					
final	166	745	140	2203	399
non-final	134	743	166	2304	461
R-colored schwa					
final	89	1082	197	1936	267
non-final	74	943	213	2014	287

Table 6: Means and standard deviations for vowel formants in schwa-only syllables and R-colored schwa across the two prosodic conditions (phrase-final and non-final)

		F1		**F2**	
	n	Mean	sd	Mean	sd
Schwa-only					
Monolingual	145	704	152	2147	434
Bilingual	155	780	142	2343	405
R-colored Schwa					
Monolingual	81	956	238	1959	306
Bilingual	82	1081	171	1984	250

Table 7: Means and standard deviations for vowel formants in schwa-only and R-colored schwa in the monolingual and bilingual children

We conducted a linear mixed effects model to determine what factors accouted for the raw F1 formant measures. We entered as fixed effects schwa syllable type (schwa-only or R-colored schwa), phrase position (final vs. non-final), and bilingual status (mon vs. bi). We did not enter word-length because we did not anticipate formant frequency differences due to this variable. Random effects included random intercepts for participants and items. There were 463 individual formant measures. Results indicated that all three factors contributed significantly to model fit: schwa syllable type (β=285.90, se.=17.91, $\chi^2(1)$=177.25, p<.001), phrase position (β=-57.25, se.=16.15, $\chi^2(1)$=12.293, p<.001) and bilingual status (β=94.55, se.=27.38, $\chi^2(1)$=6.74, p<.01). The F1s of schwa-only syllables were significantly lower than the F1s of R-colored schwa (suggesting more closed production); the F1s in phrase-final position were significantly higher than those in non-final position (suggesting more open production) and the F1s of bilinguals were significantly higher than those of monolinguals (suggesting more closed production). In addition, there was a significant interaction between syllable-type and position ($\chi^2(1)=11.15$, $p<.001$), meaning that schwa-only syllables differed from R-colored schwa in terms of the influence of phrase position. As can be seen in Table 6, the F1s of schwa-only syllables hardly differed between final and non-final position ($z=-.78$, $p=.86$) but the F1s of R-colored schwa did ($z=-4.86$, $p<.001$). R-colored schwas became less open in non-final position.

In the next analysis, we conducted a linear mixed effect model on the normalized F1 measures. Results indicated that schwa syllable type ($\beta=.36$, se.=.02, $\chi^2(1)=172.20$, $p<.001$) and position ($\beta=.07$, se.=.02, $\chi^2(1)=11.60$, $p<.001$) remained significant but bilingual status did not ($\beta=.03$, se.=.04, $\chi^2(1)=.40$, $p=.53$). This suggests that the higher raw F1 values of the bilinguals came about from idiosyncratic vocal tract differences but not from systematic differences due to bilingualism. The interaction between syllable-type and position remained significant ($\chi^2(1)=8.92$, $p<.01$) indicating that position influenced F1 vowel measures differently for schwa-only versus R-colored schwa.

Mixed effect models conducted on the raw and normalized F2 measures revealed only one significant factor in both models: schwa syllable type (raw F2: $\beta=-255.41$, se.=40.94, $\chi^2(1)=35.27$, $p<.001$; normalized F2: $\beta=.13$, se.=.02, $\chi^2(1)=35.77$, $p<.001$). The F2s of schwa-only syllables were significantly higher than those of R-colored schwa suggested a more fronted position of the tongue. There were no differences in the F2s across different phrase positions or between monolingual and bilingual children.

Using the stat-ellipse function and ggplot program in R, we plotted a series of vowel ellipses contrasting schwa-only, R-colored vowels and other referent vowels.[11] Figure 4 presents the vowel ellipses for schwa-only and R-colored schwa when all individual data points were plotted across monolingual and bilingual children. R-colored schwa was characterized by a wide dispersion of F1 values but a compact distribution of F2. Schwa-only syllables were characterized by a wide dispersion of F1 and F2 values, particularly of F2. Figures 5 and 6 display the effect of phrase-position on schwa-only and R-colored schwa. As can be seen, the effects of phrase position were stronger for R-colored versus schwa-only syllables. Non-final position resulted in lower F1 values for R-colored schwa (i.e., more closed position), and more variable F1 and F2 values for schwa-only syllables.

[11] The "type" function of stat-ellipse was set to "norm" thus assuming a multivariate normal distribution and the "confidence level" function was set to the default 0.95.

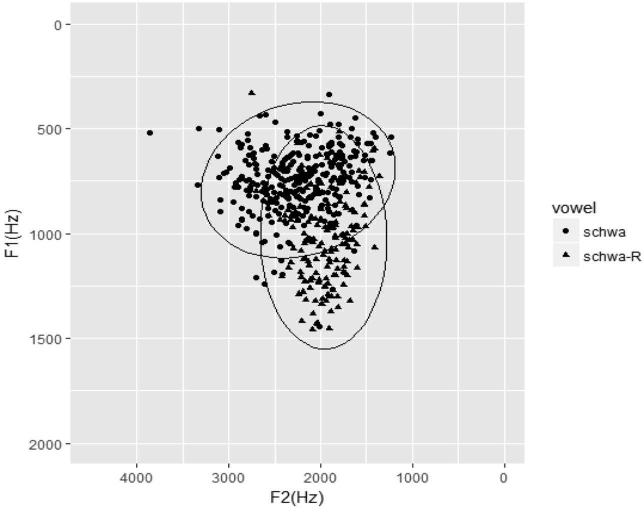

Figure 4: Vowel ellipses plotting individual vowels formants for schwa-only and R-colored schwa.

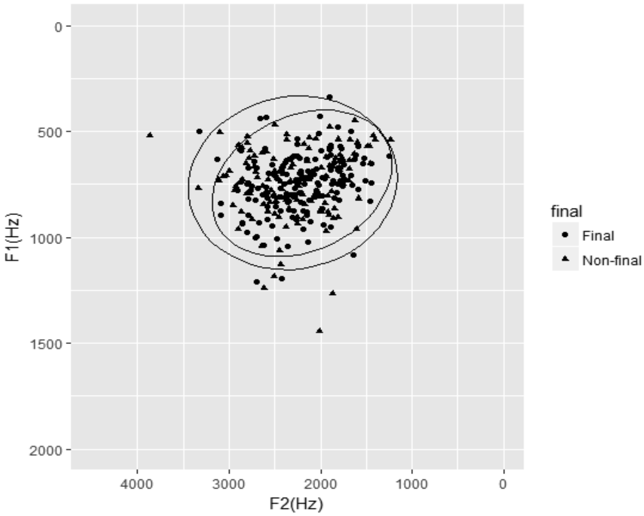

Figure 5: Vowel ellipses plotting individual vowels formants for schwa-only across phrase-final and non-final positions. Non-final refers to the largest ellipse.

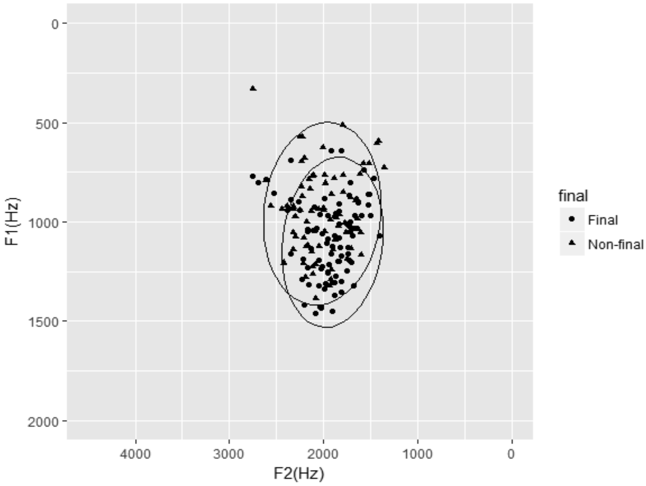

Figure 6: Vowel ellipses plotting individual vowels formants for R-colored vowels across phrase-final and non-final positions. Final refers to the ellipse with the highest F1 values.

Figure 7 presents the vowel ellipsis for schwa [ə] alongside that of [ɪ] and [ɛ] for the monolingual and bilingual children. We focus on vowels [ɪ] and [ɛ] because they have vowel qualities similar to [ə] and were frequently attested in the corpus (in contrast to vowels [ø, œ]). In particular, vowel [ɛ] is the most frequently transcribed vowel for target [ə] at the earliest stages of acquisition (Kehoe & Lleó 2003). Figure 7 shows that the vowel space for schwa is large (i.e., larger than for vowels [ɪ] and [ɛ]) and overlaps the vowel spaces of [ɪ] and [ɛ] in the mid-center. Figure 8 displays the vowel space for schwa [ɐ] alongside that of [a] in the monolingual and bilingual children. We focus on [a] because it has the vowel quality the most similar to R-colored schwa. Figure 8 shows that the vowel space of [ɐ] completely covers the vowel space of [a] but also extends higher including vowels of a more closed quality.

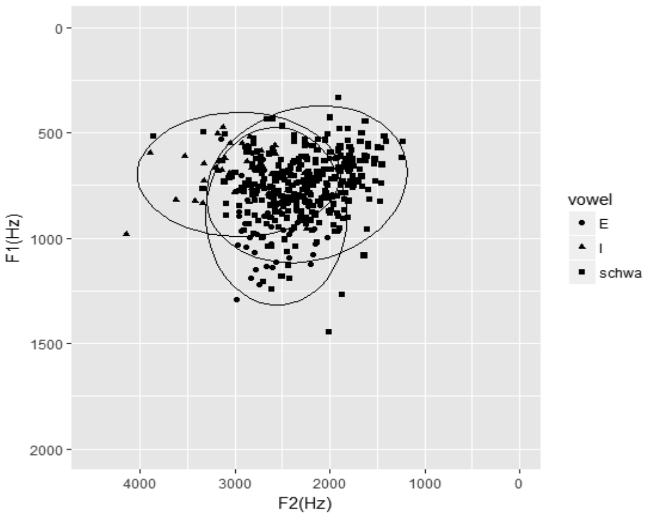

Figure 7: Vowel ellipses plotting individual vowels formants for schwa and referent vowels [ɪ] and [ɛ].

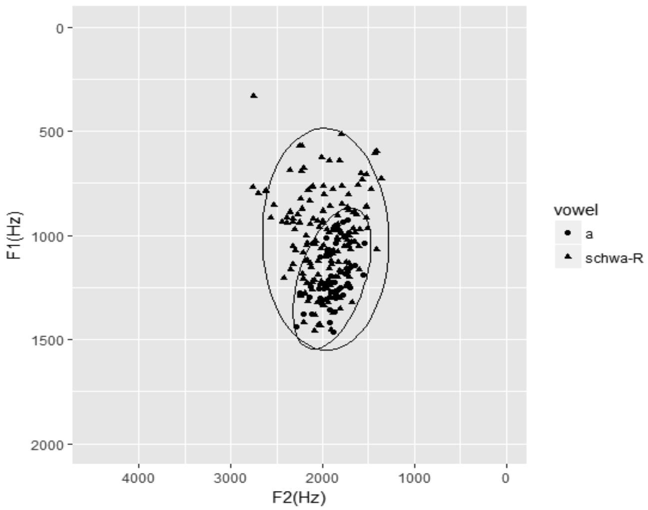

Figure 8. Vowel ellipses plotting individual vowels formants for R-colored schwa and referent vowel [a].

In sum, statistical analyses revealed that children distinguished the two vocalic schwas in terms of formant frequency values, producing [ə] with lower F1s and higher F2s than [ɐ]. They also realized [ɐ] with higher F1s in phrase-final position (i.e., more open) than in non-final position but they did not distinguish the F1s of [ə] in terms of phrase position. There was no influence of phrase position on F2s for either schwa syllable. Bilinguals did not differ from monolinguals in their formant frequency realizations of schwa syllables when normalized measures were taken into consideration.

3.3 Target syllabic consonants

In a final analysis, we examined children's productions of syllabic consonants. First, we determined the percentage of target syllabic consonants which were realized as a vowel plus consonant. These results are shown in Table 8 separated out according to whether the child was monolingual or bilingual and whether the target syllabic consonant was /l/ or /n/. A production containing vowel and consonant was observed more frequently in the bilingual (49% or 55/112) versus monolingual productions (9% or 13/147) and for syllabic /n/ (31% or 60/194) versus syllabic /l/ (12% or 8/65). Chi square analyses indicated that the difference between the bilingual versus monolingual children was highly significant ($\chi^2(1)=53.23$, $p<.001$) as was the difference between syllabic /n/ and /l/ ($\chi^2(1)=8.71$, $p<.01$). It must be noted, however, that the high number of epenthetic vowels in the bilingual children came from one child in particular, Simon.

Child	Target syllabic /l/ %	Target syllabic /n/ %
Monolinguals		
Britta	6% (1/18)	13% (4/30)
Marion	6% (1/16)	9% (4/44)
Thomas	0 (0/10)	10% (3/29)
Total	5% (2/44)	11% (11/103)
Bilinguals		
Simon	50% (5/10)	74% (34/46)
Jens	0 (0/7)	27% (4/15)
Manuel	25% (1/4)	37% (11/30)
Total	29% (6/21)	54% (49/91)

Table 8: Percentages of target syllabic consonants produced with vowel plus consonant in the monolingual and bilingual children. Individual child data is shown.

Finally, we investigated the acoustic qualities of the epenthetic vowel. Its mean length was 126 ms (sd=53) which was slightly shorter than the mean duration of schwa only syllables (i.e., 137 ms, see Table 1). Its formant values (F1 = 745 Hz; F2 = 2229 Hz), however, were very similar to those of schwa-only syllables (i.e., F1=744 Hz; F2=2248 Hz, see Table 5). The presence of the epenthetic vowel increased the length of the syllables. Syllables without epenthetic vowels were shorter (Mean=177.02 ms; sd=69.06) than those containing epenthetic vowels (Mean=232.87 ms; sd=69.54). We re-conducted our statistical analyses in order to determine if there was still a significant difference between the duration of syllabic consonants and other schwa syllables once we excluded those items containing epenthetic vowels. Results indicated that type of schwa syllable remained a significant factor in models using both raw duration (χ^2=23.68, p<.001) and normalized measures (χ^2=21.75, p<.001). In all analyses, significant differences were observed between syllabic consonants and schwa-only syllables (raw duration: z=4.94, p<.001; $ratio_{stress/unstress}$: z=-4.59, p<.001). In the raw duration measures, syllabic consonants were also longer than syllables containing R-colored schwa (z=-2.78, p<.05); in the normalized measures, significant differences were observed between the $ratio_{stress/unstress}$ of schwa-only syllables and R-colored schwa (z=-2.78, p<.05).

To sum up the section on syllabic consonants, children realized target syllabic consonants as syllabic consonants most of the time (i.e., 74% or 191/259). Productions containing a vowel and consonant occurred more often in the bilinguals than the monolinguals and when the target syllabic consonant was /n/ rather than /l/. The epenthesized vowel had similar acoustic qualities to schwa-only syllables in terms of duration and formant frequency characteristics. When statistical analyses were re-conducted after excluding all items with epenthesized vowels, syllabic consonants were still found to be longer than schwa-only and R-colored schwa.

4 Discussion

This study examined the acoustic qualities of schwa syllables in monolingual and bilingual children. We looked at three types of information which might shed light on the acquisition of schwa. First, we examined the acoustic qualities of different types of schwa syllables. We found that schwa-only syllables were shorter than R-colored schwas which were in turn shorter than syllabic consonants. Schwa-only syllables had different formant frequency values to that of R-colored schwa. As for target syllabic consonants, they were mainly realized as syllabic consonants, and if they were realized as vowel + consonant, the acoustic qualities of the vowel resembled that of schwa.

Second, we examined whether the acoustic correlates of schwa differ according to word length and phrase position. Our results showed that word length had a minimal effect on schwa duration but phrase position did have an effect. Schwa syllables were longer in phrase-final than in non-final position, although a significant interaction effect (in the normalized measures) indicated that it was schwa-only syllables which were conditioned by phrase position and not the other schwa syllables. Phrase position did not influence the formant frequency values of schwa-only syllables but it did influence those of R-colored schwa.

Third, we examined whether bilingual children differ from monolingual children in their acoustic realization of schwa. The bilingual children produced schwa syllables with similar duration and formant frequency values to monolingual children. The only difference was that they realized target syllabic consonants more frequently with a vocalic nucleus than monolingual children did. In the following paragraphs, we summarize the results of the study in more detail and then discuss what they say about the acquisition of schwa.

4.1 Phonetic differences in schwa syllables

4.1.1 Duration

A salient finding of the study was that the duration characteristics of schwa syllables are different. Schwa-only syllables and syllables with R-colored schwa are significantly shorter than syllables with syllabic consonants (e.g., schwa: 138ms, R-colored schwa: 149 ms vs. syllabic consonants: 193ms). This was found to be the case across raw and normalized duration measures and even when forms with epenthesized vowels were excluded from the set of syllabic consonants. In terms of rhythmic pattern, the $ratio_{stress/unstress}$ of 1.62 would suggest a SW pattern for stressed syllable + schwa-only syllable, whereas the $ratio_{stress/unstress}$ of 1.12 would suggest an equal prominence pattern for stressed syllable + syllabic consonant. If we assume that syllable timing is the unmarked rhythmic pattern for children (Allen & Hawkins 1980; Bunta & Ingram 2007), then schwa-only syllables pose a greater challenge rhythmically than syllabic consonants. Our raw duration measures did not indicate significant differences between schwa-only and R-colored schwa; however, our analyses based on ratio measures indicated that the ratio between stressed and unstressed syllable was significantly greater for schwa-only syllables than for R-colored schwa (1.62 vs. 1.34), suggesting some prosodic differences between these two types of syllables as well.

4.1.2 Formant frequency

Children realized schwa-only syllables with F1s and F2s of 744 Hz and 2248 Hz and R-colored schwa with values of 1019 Hz and 1971 Hz. As expected, these values are considerably higher than those obtained for adult speech (see values reported by Patzold & Simpson 1997; Zimmerer & Reetz 2011) and reflect the influence of vocal tract growth on vowel formants (Vorperian & Kent 2007). The formant values for R-colored schwa are not dramatically different, however, from those reported for the central vowel [ʌ] produced by three-year-old English-speaking children (F1: 890; F2: 2029, see McGowan et al. 2014, Table 3). We cannot make direct comparisons with other literature findings due to the lack of developmental studies on the acoustics correlates of schwa vowels (see however Yuen, Demuth, & Davies 2012 for information on [ə] in American English two-year-olds).

Our finding of significant differences between the formant values of schwa only and R-colored schwa replicates other studies which show that, by three years, children produce individual vowels with distinct vowel qualities (McGowan et al. 2014). It might have been anticipated that children could distinguish full vowels acoustically by three-years but not reduced vowels [ə] and [ɐ] because of their centralized vowel quality and their presence in unstressed syllables only. However, this was not found to be the case.

Inspection of Figures 7 and 8 indicates quite different vowel ellipses for [ə] and [ɐ]. Schwa-only syllables were characterized by a wide dispersion of F1 and F2 values, especially of F2. They partially overlapped the vowel ellipses of the full vowels [ɪ] and [ɛ], although [ɪ] was shown to have higher F2 values (more front quality) and [ɛ] to have higher F1 values (more open quality) than [ə]. R-colored vowels were characterized by a wide dispersion of F1 values. They completely covered the vowel ellipsis of the full vowel [a] but their F1s were lower (more close quality) and extended into the central region.

These vowel ellipses provide a good indication that three-year-old children are able to produce target schwa syllables as centralized vowels but they are not able to do so all the time. Some of the time, they produce target schwa syllables with the same acoustic qualities as full vowels. This is consistent with transcription studies which report that children often substitute target schwa with full vowels. Kehoe and Lleó (2003) did not find that full vowel production was very common in children at the age of three years. It was present approximately 12% of the time. Nevertheless, native speakers transcribed target schwa as schwa only 42% of the time. They often chose to transcribe target schwa (46% of the time) as a centralized [ɛ]. Our acoustic results support the transcription findings in showing a great deal of overlap between the vowel spaces of target schwa and full vowels.

4.1.3 Target syllabic consonants

The analyses of syllabic consonants focused on whether children realized them with a vocalic element. It was found to happen on a minority of occasions (i.e., 26%) meaning that children realized target syllabic consonants as syllabic consonants most of the time. The presence of the vocalic element was conditioned by the following consonant (/n/ vs /l/) and whether the speaker was monolingual or bilingual. Toft (2002) also showed that syllabic /l/ and /n/ patterned differently, with syllabic /n/ being realized more often as /Cən/ than syllabic /l/. Our child results are consistent with the adult ones.

We cannot determine whether the 74% schwa deletion rate found in this study is representative of child speech given the limited developmental research in this area. Kasuya and Arai (2013) report that German native speakers delete schwa 52% of the time when speaking at a normal speech rate and 11% of the time when speaking at a slow rate (in a /Cən/ context). Thus the value of 74% seems high given that the children would be speaking at a slower rate of speech than adults. One possibility is that there are dialectal differences in schwa deletion and the children's input could have contained higher schwa deletion rates than suggested by the study of Kasuya and Arai (2013). Nevertheless, findings on the acquisition of schwa in French show that children are more likely to produce the variant with schwa even when they exposed to input forms in which schwa is absent (Andreassen 2013). Overall, these findings support the transcription results of Kehoe and Lleó (2003) in which the latter stage of acquisition for target syllabic consonants is characterized by realization of a syllabic consonant rather than schwa plus consonant. The ease at which children acquire syllabic consonants is surprising given that they are not frequent amongst the world's languages (Bell 1978) and thus could be considered marked elements. However, data on the articulatory dynamics of syllabic consonants show that are characterized by non-overlapping articulatory gestures (Pouplier & Beňuš 2011) which may make them easier to realize for children than short highly co-articulated vocalic segments such as schwas.

Pouplier and Beňuš (2011) also observe that syllabic liquids are produced with a tongue retraction gesture that provides a sonority peak for the syllable. They cite the work of Krakow (1999) which shows that syllabic nasals have a velum gesture which is analogous to the retraction gesture for syllabic liquids. In our acoustic measures, we also observed that children's productions of syllabic liquids and nasals were often characterized by a sonority peak or vocoid section akin to the retraction gesture discussed by Pouplier and Beňuš (2011). This could mean that syllabic consonants function similarly to vocalic nuclei in terms of their sonority make-up and, thus, do not constitute "defective syllables" as such. Further investigation is needed to determine what the articulatory features of syllabic consonants are which make them phonetically simple structures for children.

Application of Andreassen's (2013) findings on French schwa to the current German data might lead us to expect that after a period in which children's speech is subject to phonological (developmental) constraints which result in a high degree of syllabic consonant production, children's speech would then be subject to stylistic constraints. In this case, we might expect to see greater schwa realization in keeping with the dialectal variation in the child's input. Further research of a longitudinal nature is needed to confirm whether children's schwa realizations for target syllabic consonants gradually approximate the dialectal patterns of the input.

4.2 Factors influencing schwa production

4.2.1 Duration

Word length. Duration differences of schwa syllables according to word-length were not very present in the data. Schwa syllables were on average 10 ms longer in two-syllables versus multisyllabic words but this was not a significant difference. The lack of a word length effect in the current study could be due to several factors. First, we did not control for phrase length. For example, a two-syllable (or multisyllabic) word (e.g., Wasser "water") could have constituted a phrase on its own or could have been embedded in a larger phrase (e.g., Wass[ɐ] "water" vs. das unter Wass[ɐ] "that under water"). If phrase length also influences duration of schwa syllables, this would have led to uncontrolled effects for both categories of word length. Second, our definition of multisyllables was large and included three- to five-syllable words. This may have also led to reduced differences between the two categories of word length. Third, decisions of what constituted a multisyllabic word or phrase were at times difficult to make. We relied on prosodic cues such as pitch accent to determine whether children were producing noun phrases or compound words (e.g., Kohlewagen "coal waggon" was interpreted as compound word akin to Kinderwagen "pram" and not as a noun phrase akin to kleine(r) Wagen "small waggon"); however our assumptions may not have been the same as the children's intentions. Furthermore, compound words may be interpreted by children as two separate words, again, lessening the prosodic differences between two-syllable and multisyllabic words.

Phrase position. Duration differences of schwa syllables according to phrase position were present in the data. Schwa syllables were on average 46 ms longer in phrase-final in comparison to non-final position. Inspection of the duration characteristics of different schwa syllables according to phrase position (see Appendix D) reveals that the conditioning effect of phrase position was stronger for schwa-only syllables than for R-colored schwa and syllabic consonants (51 ms difference for schwa-only syllables vs. 39 ms difference for R-colored schwa and 26 ms for syllabic consonants). In the case of the ratio measures, schwa-only syllables varied according to phrase position but not the other schwa syllables. Children seemed to have greater difficulty reducing the phonetically "heavier" schwa syllables in phrase internal positions. We cannot exclude, however, that the absence of a phrase position effect for R-colored schwa or syllabic consonants in the ratio measures came about from methodological factors. There were fewer productions of R-colored schwa and syllabic consonants in non-final position reducing statistical power (see Appendix B).

Phonological vowel length. Although not a focus of the study, our results have some bearing on children's acquisition of vowel length. Phonological vowel length had a strong influence on the normalized duration measures. Results showed that the stressed syllable was about the same length as the schwa syllable when it was phonologically short (ratio=1.0). It was longer than the schwa syllable when it was phonologically long (ratio=1.6). The fact that this variable was highly significant in our model suggests that children, aged three-years, have already developed some control over phonological vowel length.

4.2.2 Formant frequency

Phrase-position. Studies by Flemming and colleagues in English have argued that the acoustic qualities of schwa differ greatly in word-final versus word-medial position (Flemming, 2009; Flemming & Johnson, 2007). Indeed, they argue for two different types of schwa: Word-final schwa has a narrowly defined F2 but a wide dispersion of F1; word-medial schwa has a narrowly defined F1 and a wide dispersion of F2. In our study, we considered the effects of phrase position rather than word position. It might be assumed that our category of non-final schwa may pattern with Flemming's (2009) word-medial schwa in terms of coarticulatory effects in child speech.

In the current study, we did not find strong effects of phrase position on the formant values of schwa syllables. The only exception was for the F1s of R-colored schwa, which were higher in final position (more open quality), a finding which goes in the direction of Flemming's (2009) results. Interestingly, the formant patterns of R-colored schwa and schwa-only syllables resemble those of English schwa in word-final and -medial position respectively. R-colored schwa is similar to word-final English schwa in showing little dispersion in F2 and wide dispersion in F1. Schwa-only syllables are similar to word-medial English schwa in showing wide dispersion in F2. We could postulate that word-final English schwa has a quality not unlike German [ɐ] (sometimes transcribed as [ʌ]) whereas word-medial English schwa more closely resembles German [ə]. The reason why we did not observe strong differences according to phrase position in German schwa syllables could be due to the fact that they would compromise the functional differences between [ə] and [ɐ]. If phrase position influenced German schwa syllables to the same degree as in English, target schwa-only syllables in final position might sound like R-colored schwa and target R-colored schwa in non-final position might sound like schwa-only syllables.

Our findings are not consistent with Levelt's (2008) proposal that children augment utterance-final schwas to full vowels. We observed that children realized duration differences between utterance-final and non-final schwa but not vowel quality differences. It is possible that the children we measured were beyond the stage of full-vowel augmentation for schwa, but the transcription results of Kehoe and Lleó (2003) indicate that full vowel augmentation occurs to a small extent even at this stage.

4.3 Acquisition of schwa by bilingual children

Our analyses showed very few differences in the realization of schwa syllables related to bilingualism. The bilingual children had almost identical raw duration measures as the monolingual children. The normalized duration measures were slightly reduced compared to the monolinguals: the differences between stressed and schwa syllables, and specifically between phonologically long stressed and schwa syllables were smaller in the bilingual compared to monolingual children, but these differences did not reach significance.

In the case of vowel formant measures, we documented significant differences in raw F1 values between monolingual and bilingual children (see also Kehoe & Lleó 2017); however, when we repeated the analyses with normalized F1 values, these differences disappeared. Thus, we interpret the earlier significant result as one reflecting idiosyncratic vocal tract differences rather than an effect of bilingualism.

The main result which appeared to reflect monolingual-bilingual differences was that bilingual children epenthesized vowels more frequently than monolingual children when realizing target syllabic consonants (49% vs. 9%). This result is consistent with others studies in second language acquisition which show that non-native speakers, whose L1 does not contain syllabic consonants, realize target syllabic consonants more frequently with a vocalic element (Gut 2003; Kasuya & Arai 2013). Nevertheless, we interpret this result cautiously since the instances of vowel epenthesis came from one bilingual child in particular, suggesting idiosyncratic effects alone or in combination with the influence of bilingualism. We also cannot exclude the fact that input effects may be responsible for the higher rate of schwa preservation in the bilingual group. These children may be exposed to more frequent productions of schwa + consonant variants spoken by non-native speakers in their surroundings (Mayr & Montanari, 2015).

At first glance, these results appear to differ from previous studies on the acquisition of rhythm and vowel reduction with the same set of bilingual children which showed some influence of bilingualism (Kehoe, Lleó, & Rakow 2011; Kehoe & Lleó 2017). However on closer inspection, the apparent differences can be reconciled. In the earlier studies, the bilingual effect came about from cross-linguistic comparisons. These studies documented significant differences between the rhythmic indices (or $\text{ratios}_{\text{stress/unstress}}$) of the respective monolingual populations (i.e., Spanish and German) but not between the rhythmic indices (or $\text{ratios}_{\text{stress/unstress}}$) of the two languages of the bilingual children. There appeared to be a merging of the two rhythmic patterns in the bilingual children (see also Mok 2011). These studies did not observe strong monolingual-bilingual differences (in comparisons between monolingual German vs bilingual German) as was also the case in the current study.

Mok (2011) observed potential differences in the vowel reduction patterns of monolingual English and bilingual Cantonese-English three-year olds. She compared the children's production of the lax vowel [ɪ] in the English word "this" when realized in non-focus-bearing position. Vowel formant measures showed that the bilingual children produced the vowel /ɪ/ with more extreme values and more variable quality than the monolingual children, suggestive of less vowel reduction. Mok's (2011) bilingual children were for the most part Cantonese-dominant; the bilingual children in the current study were not German-dominant but they were growing up in a German-speaking environment. Dominance or ambient-language effects may explain the presence of differences in Mok's (2011) study and the lack of them in the current one.

Overall, the findings suggest that schwa when acquired at an early age does not pose a speech production challenge for bilingual children, consistent with the findings of other investigators (Byers & Yavas 2016). There were some subtle effects of reduced prominence in the bilingual children as compared to the monolingual but these effects were minimal compared to the large effects due to schwa syllable type and phrase position.

4.4 A return to the acquisition of schwa syllables

Finally, a goal of the study was to determine whether the acoustic results could shed light on the difficulties children face in the acquisition of schwa. Before we address this question, we first ask a more central question "do schwa syllables pose difficulty in acquisition?" Several of the findings in this study are consistent with children having adult-like control over schwa suggesting that schwa may not be as difficult as originally supposed. Children distinguished schwa-only and R-colored schwa in terms of formant structure. They also displayed conditioning effects according to phrase position for certain schwa syllables (duration: schwa-only syllables; F1: R-colored schwa). Furthermore, bilingual children did not experience difficulty acquiring schwa-only and R-colored schwa, which might have been expected given that their exposure to schwa was reduced in comparison to monolingual children.

Nevertheless, several findings of the study are less consistent with adult-like control. Children did not make schwas longer in two-syllable versus multisyllabic words. They did not produce R-colored schwa and syllabic consonants longer in phrase-final versus non-final position. Bilingual children differed from monolingual children in their acquisition of target syllabic consonants producing more variants with vowel plus consonant than syllabic consonant. In short, the findings show that children, aged 3,0, are still in the process of developing fine control over schwa production.

Second, our comparison of the acoustic characteristics of the three-schwa syllables suggests that it is schwa-only syllables that create the greatest acoustic challenge for children. They are significantly shorter than the other schwa syllables, which leads to a more marked rhythmic (i.e., stress-timed) pattern when they are produced in running speech. If the acquisition of schwa is viewed within the larger theme of vowel reduction and rhythm, schwa-only syllables are rhythmically more complex than the other schwa syllables.

Schwa-only syllables are also characterized by considerable formant frequency variability, particularly of F2. Studies on schwa in adult speech also report considerable variability of F2, which increases when schwa becomes shorter as in word-medial position (Flemming, 2009). The difference between the child and adult data resides in the fact that a high degree of F2 (and F1) variability was present in phrase-final and non-final position, and regardless of whether schwa was long or short (161 ms in phrase-final & 110 ms in non-final position; see Appendix D). At this point, we cannot determine whether the high degree of formant frequency variability reflects perceptual or production difficulties (i.e., the perceptual ambiguity of schwa or the productive challenge of producing a highly co-articulated vowel). In either case, it is hardly surprising that target schwa is sometimes transcribed as a full vowel since it occupies a large vowel space which overlaps with many full vowels. The same was not true of R-colored schwa in the current data which had a more defined mid-central quality.

5 Conclusion

This study investigated the acoustic characteristics of schwa syllables in three-year old German monolingual and bilingual children. Our study showed that schwa syllables were characterized by different duration and formant frequency characteristics. Schwa-only syllables are short and are characterized by a wide range of F2 values; R-colored schwas are slightly longer than schwa-only syllables and are characterized by a wide range of F1 values; syllabic consonants are longer than schwa-only and R-colored schwa. In this study, they were sometimes realized as schwa plus consonant (26% of the time) but mostly realized as syllabic consonants. Our study documented significant differences in the duration of schwa syllables according to phrase position, although this effect was mainly seen with schwa-only syllables. Differences in duration due to word length were minimal in this study.

The study did not document many differences in schwa realization pertaining to bilingualism suggesting that young bilinguals are not at a disadvantage in the production of schwa. Finally, we focused on the acoustic challenge of acquiring schwa-only syllables in comparison to other schwa syllables, which may relate to their reduced length, their more marked prosodic pattern, and their variable formant frequency realizations.

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Appendix A

Some of the most frequent words containing schwa syllables in the data-base. The words are displayed according to whether they contained schwa-only, R-colored schwa or syllabic consonants, whether they occurred in two-syllable or multisyllabic words and whether they occurred in word-final or non-final position.

Schwa		**R-colored schwa**		**Syllabic Consonants**	
Two-syllable	**Multisyllabic**	**Two-syllable**	**Multisyllabic**	**Two-syllable**	**Multisyllabic**
			Word-final[a]		
Affe	alleine	Becher	Birnefresser	Augen	anrufen
alle	Badewanne	besser	Gabelfresser	Boden	Antilopen
Beine	Banane	Butter	Gießkann(e)-fresser	diesen	aufgeblasen
beste	Bohrmaschine	Dampfer	Holzfäller	draußen	aufgegessen
Brille	draufstelle	dicker	Hubschrauber	drucken	aufmachen
danke	Elefante	Donner	(Ka)setten-rekorder	Entchen	Bademantel
deine	Frederike	drüber	Kopfhörer	essen	darübersteigen
dicke	Garage	Eier	Korbfresser	fliegen	Elefanten
diese	Gießkanne	Eimer	Kuscheltücher[b]	Flügel	gefliegen[b]
eine	Giraffe	Feder	Marienkäfer	Gabel	gefunden
Ende	Haltestelle	Feuer	Puppenfresser	Garten	geschnitten
Ente	Kapuze	Finger	Schaufelbagger	(ge)gessen	geschrieben
Fische	Karotte	Fresser	Schraubenzieher	großen	gestanden
gelbe	Krokodile	großer	Schuhfresser	Häschen	getrunken
Glocke	Libelle	immer	Schuhschrauber	Himmel	geworden
große	Lokomotive	Käfer	Sternfresser	Igel	hingefahren
Haare	Pistole	Keller		kaufen	Kaffanbüffel
Hause	rausnehme	Kinder		Kugel	kaputtmachen
Jacke	Schokolade	Klammer		laufen	Kindergarten
Katze	Spritzepistole	Koffer		legen	Kinderwagen
keine	Stachelbeere	Kracker		Löffel	Kohlewagen
kleine	Steinpilze	lecker		Löwen	Krankenwagen
knete	Trompete	Leiter		machen	Leoparden

Lampe		Löcher		oben	nassgeworden
Löwe		Mutter		Puzzel	Puppenwagen
Maire		Panther		Regen	reingeflogen
meine		Räder		Rüssel	Gummibärchen
Nase		runter		Sachen	runtergefallen
Puppe		schneller		schienen	Tankwagen
Rote		Schrauber		schlafen	übernachten
Schere		Sommer		schlucken	umgefallen
Schiene		Tiger		Schlüssel	runterfallen
Schlange		Trecker		sitzen	verstecken
Schnecke		unter		spielen	
Straße		Wasser		unten	
viele		wieder		Vogel	
welche		Zucker		Wurzel	
Non-final					
Besuch	abgeholt	versteckt	ausverkauft		Apfelsaft
gebracht	angedampft		darübersteigen		Dosenmilch
geguckt	aufgeblasen		Feuerschiff		Eidelstadt
gehört	aufgegessen		Feuerwehr		Eisenbahn
gemacht	aufgewacht		Kindergarten		Gabelfresser
geparkt	ausgemalt		Kinderwagen		Gockelhahn
Geschenk	Bademantel		Lederjacke		Kettensäge
geschrieb	Badewanne		Pettersson		Krankenwagen
gesteckt	Birnefresser		Reißverschluss		Kuscheltuch[b]
gewascht	draufgedreht		runterfahren		Kuscheltücher[b]
	festgenäht		runtergefallen		Menschenhaus
	gebacken		runterschmeißen		Nagelfeile
	gefahren		Schmetterling		Puppenbaby
	gefliegen[b]		Sommerkleid		Puppenfresser
	gefunden		übernachten		Puppenwagen
	gegangen		unterfallen		Schaufelbagger
	geschnitten		wiedersehen		Schrauben-zieher
	geschrieben				Segelboot
	gesehen				Stachelbeeren
	gestanden				Straßenbahn

	getrunken					
	Haltestelle					
	hingefahren					
	Kohlewagen					
	nassgeworden					
	reingeflogen					
	reingenommen					
	runtergefallen					
	umgefallen					
	vorbeigefahren					
	zugemacht					

a. The words are displayed according to whether the schwa syllable was in word-final or non-final position. In the study, we examined schwa syllables in utterance-final versus non-final position. Schwa syllables in word-non-final position would have always been utterance non-final but word-final schwa syllables could have been utterance-final or non-final depending upon where the word appeared in the utterance.

b. Some words were produced by the children although they are not strictly speaking grammatical or would appear in a German dictionary.

Appendix B

Numbers of schwa syllables analyzed for the monolingual and bilingual children.

Schwa-only

Children	Total	SW_{final}	$SW_{non\text{-}final}$	$Multi_{final}$	$Multi_{non\text{-}final}$
Monolingual					
Britta	51	20	20	4	7
Marion	61	26	16	10	9
Thomas	38	20	8	0	10
Total	150	66	44	14	26
Bilingual					
Simon	71	36	11	15	9
Jens	48	17	24	2	5
Manuel	38	14	13	2	9
Total	157	67	48	19	23

R-colored schwa

Children	Total	SW_{final}	$SW_{non\text{-}final}$	$Multi_{final}$	$Multi_{non\text{-}final}$
Monolingual					
Britta	19	8	3	7	1
Marion	42	14	14	3	11
Thomas	24	10	2	4	8
Total	85	32	19	14	20
Bilingual					
Simon	44	18	5	3	18
Jens	20	15	4	1	0
Manuel	18	9	5	1	3
Total	82	42	14	5	21

Syllabic Consonant

Children	Total	SW_{final}	$SW_{non\text{-}final}$	$Multi_{final}$	$Multi_{non\text{-}final}$
Monolingual					
Britta	48	21	11	8	8
Marion	60	25	10	13	12
Thomas	39	18	3	11	7
Total	147	64	24	32	27
Bilingual					
Simon	56	26	3	14	13
Jens	22	14	3	3	2
Manuel	34	18	8	8	0
Total	112	58	14	25	15

Appendix C

Means and standard deviations of raw and normalized duration measures of different schwa syllables according to word length.

	Two-syllable			Multisyllabic		
	n	Mean	sd	n	Mean	sd
Schwa-only						
raw length	225	141.22	64.80	82	127.66	65.29
$ratio_{stress/unstress}$		1.55	0.98		1.82	1.15
R-colored schwa						
raw length	107	154.21	61.84	60	140.53	43.46
$ratio_{stress/unstress}$		1.37	0.73		1.28	0.63
Syllabic consonant						
raw length	160	198.38	73.97	99	183.04	71.13
$ratio_{stress/unstress}$		1.06	0.48		1.22	0.63

Appendix D

Means and standard deviations of raw and normalized duration measures of different schwa syllables according to phrase position.

	Phrase-final			Non-final		
	n	Mean	sd	n	Mean	sd
Schwa-only						
raw length	166	161.12	68.19	141	109.91	48.51
$ratio_{stress/unstress}$		1.44	0.86		1.84	1.18
R-colored schwa						
raw length	93	166.48	62.58	74	127.70	37.34
$ratio_{stress/unstress}$		1.35	0.76		1.32	0.62
Syllabic consonant						
raw length	179	200.55	76.19	80	174.55	62.62
$ratio_{stress/unstress}$		1.16	0.57		1.04	0.48