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Phonetic correlates of tongue root vowel contrasts in Maa

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Abstract

Maa, a Nilo-Saharan language, exhibits a cross-height vowel harmony system known as ‘tongue root harmony’. The high and mid vowels participate in this system, but the low vowel does not. The Maa harmony system is briefly described, followed by an investigation into the phonetic properties of the vowels. Five Maa speakers were recorded producing 100 example words three times each. The [+ATR] vowels were found to have consistently lower first formant values and relatively less energy in the higher frequency regions than their [−ATR] counterparts. An investigation of the differences between the auditorily quite similar [−ATR] high and [+ATR] mid vowels revealed durational differences for the back vowels and much inter-speaker variation for the front vowels. Electroglottographic data obtained from one speaker indicated a slightly less constricted glottis for [+ATR] than [−ATR] vowels. This phonation difference is not readily detectable auditorily in the current data, but has been reported previously for Maa. The results contribute to typological knowledge about the phonetics of tongue root vowel contrasts, as very little data is currently available for Nilo-Saharan languages. A possible origin of stronger voice quality distinctions common to other tongue root harmony languages is offered from the theory of Auditory Enhancement.

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1. Introduction

Maa is an Eastern Nilotic language spoken in Kenya and Tanzania by upwards of 800,000 individuals (Grimes, 2003). The Nilotic family pertains to the larger Eastern Sahelian family, which in turn belongs to the Nilo-Saharan phylum (Ehret, 2001).[1] The phonology of Maa, like

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[1] Ehret (2001, p. 75) writes: “To [the grouping of Astaboran, Kir-Abbaian, and Rub] is given the name Eastern Sahelian. Its composition closely parallels that of Greenberg’s (1970) original Eastern Sudanic, but the new name better

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	[+ATR]		[-ATR]	
HIGH	i	u	ɪ	ʊ
MID	e	o	ɛ	ɔ
LOW			ɑ	

Fig. 1. Maa contrastive vowels.

that of many other Nilo-Saharan and Niger-Congo languages, is marked by a type of vowel harmony known as "tongue root harmony", with two vowel sets commonly referred to as Advanced Tongue Root ([+ATR]) and Non-Advanced Tongue Root ([−ATR]). No articulatory studies have confirmed tongue advancement or pharyngeal expansion in Maa. Nonetheless, the labels [+ATR] and [−ATR] are used in the current paper for convenience of reference. Maa is a register tone language with high and low tones and tones may sometimes combine to produce tonal contours. Impressionistically, Maa appears to have an alternating strong–weak stress pattern, but this is not accompanied by any change to vowel quality.

Phonologically, Maa has nine contrastive vowels, which divide into two cross-height harmony sets, indicated in Fig. 1 (cf. Tucker & Mpaayei, 1955, p. xiv). The vowel/ɑ/ is to some extent "neutral" in that it can co-occur with vowels from either [+ATR] or [−ATR] set (cf. Wallace-Gadsen, 1980), though harmony processes mark it as a [−ATR] vowel. Such a system is said to be a "five-height" system, as the high and mid [−ATR] vowels are in general slightly lower than their [+ATR] counterparts.

The purpose of this paper is to document the acoustic phonetic properties of the Maa vowels and to determine what phonetic cues are likely to signal the ATR contrasts. Some preliminary electroglottographic data investigating voice quality correlates of the ATR contrast is also presented. A description of ATR in Maa is of phonetic typological interest as, to date, little acoustic phonetic work has been done on any Nilo-Saharan languages. Certainly, the phonetics of one ATR harmony language may not match the phonetics of another ATR language. For example, Casali (2003) notes that in five-height ATR systems, the vowels /ɪ/ and /ʊ/ may sound either more like/i/ and /u/, or more like /e/ and /o/, depending on the language. Some anecdotal evidence concurs with interlinguistic variation: A linguist, a native speaker of Akan, listening to a native speaker of Maa, could not distinguish the Maa ATR vowel differences.

Of interest is whether the acoustic correlates of the ATR contrast found in other languages, such as differences in formant structure, voice quality and overall spectral slope, are also found in Maa and, if they are found, whether they covary in the same way as in previously documented languages. Specifically, it has been proposed that voice quality and tongue root advancement covary such that more breathy voice co-occurs with advanced tongue root and more creaky voice

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(*footnote continued*)
captures its fit in the subclassificatory naming system used here." Ehret's more precise classification is: Maa-Ongamo < Lotuko-Maa < Teso-Maasaian < Eastern Nilotic < Nilotic < Kir < Kir-Abbaian (which Ehret, 1983 called "Eastern Sudanic") < Eastern Sahelian (roughly equivalent to Greenberg's "Eastern Sudanic") < Sahelian < Northern Sudanic < Sudanic < Nilo-Saharan.

with non-advanced tongue root, so as to enhance the distinctiveness of the overall contrast (Kingston, Macmillan, Dickey, Thorburn & Bartels, 1997).

1.1. Overview of ATR systems: phonology

In a comprehensive study of Niger-Congo and Nilo-Saharan languages, Casali (2003) observes that the majority of African languages with ATR harmony systems have either seven vowels /i, e, ɛ, u, o, ɔ, a/ or nine vowels / i, ɪ, e, ɛ, u, ʊ, o, ɔ, a/ though a number of other inventories do exist. For example, in some five-height languages there are two low vowels which contrast for ATR, e.g., /a/ and /ɑ/ or /ə/ and /ɑ/, resulting in ten-vowel systems. Other five-height languages may have [ɑ] and [a] or [ə] just as allophones. Such inventories occur, for instance, in some Southern Nilotic languages.

In his study, Casali found that in languages with ATR contrasts among the high vowels (including five-height vowel systems of the type found in Maa), [+ATR] spreads, but [−ATR] does not. In this sense, [+ATR] is "dominant". More specifically, if a vowel within a certain phonological domain (e.g., within a word) is specified as [+ATR], then it will require that all other vowels within the relevant domain are also pronounced as [+ATR], or that in some other way [+ATR] values are imposed or maintained at the expense of [−ATR] values. In contrast, Casali finds that four-height systems which only have ATR contrasts among mid vowels are primarily [−ATR] dominant.

1.2. History of ATR in maa

Proto-Nilo-Sarahan is thought to have had a seven vowel system (Bender 1997; Ehret 2001). The reconstructed vowel system consists of both short and long *i, *e, *ɛ, *u, *o, *ɔ, *ɑ, with only the mid vowels displaying an ATR contrast. It seems that Proto-Nilotic expanded this system to a nine, or perhaps 10 vowel system in which the high vowels, and perhaps the low vowel, gained an ATR contrast (Ehret, 2001). In the modern languages, nine or 10 vowel systems with ATR harmony systems are found in all of the Eastern, Southern and Western branches of the Nilotic family (cf. Ehret, 2001, among others), and Rottland (1982) reconstructed a 10 vowel system for Southern Nilotic including two distinct low vowels that contrasted for ATR.

Ehret (2001, p. 49) posited a nine-vowel system for Proto-Eastern Nilotic, the branch to which Maa belongs, including loss of the earlier length distinction. He claimed that [−ATR] high vowels /ɪ/ and /ʊ/ developed from short *i and *u, and also from allophones of *ɔ and *ɛ in the environment of nasal clusters, and that [+ATR] /i/ and /u/ developed from long *iː and *uː (pp. 46, 49). Presenting a different reconstruction, Vossen (1982, p. 299) wrote that Proto-Eastern Nilotic likely had ten vowels, including an ATR contrast among the low vowels. However, he noted that the reconstruction of two low vowels is "problematic" and his representation of both the low [+ATR] and low [–ATR] vowel is simply *a (all other reconstructed vowels are given distinct representations). His reconstruction of ten vowels for Proto-Eastern Nilotic was largely based on the fact that the Eastern Nilotic language Bari has ten contrastive vowels.

If Proto-Eastern Nilotic had a 10 vowel system, then modern Maa must have completely lost any phonetic (as well as phonological) contrast between two low vowels, at least insofar as formant frequencies are indicative.

Given the proposed historical development of the [+ATR] high vowels from long vowels and the [–ATR] high vowels from short vowels, the question arises whether ATR vowel pairs are currently differentiated by vowel length in Maa.

1.3. Maa ATR harmony

Evidence that the vowel inventory of Maa has two phonological sets functioning in a harmony system comes from a number of morphophonemic variations (see Archangeli & Pulleyblank, 1994; Cole, 1991; Cole & Trigo, 1988; Levergood, 1984, 1987; Wallace-Gadsden, 1980 for phonological analyses of Maa). As in many other Nilo-Saharan languages, [+ATR] is "dominant" in Maa in the sense that if any morpheme is lexically [+ATR], other morphemes within the relevant phonological domain will also display the [+ATR] feature. That is, there are some morphemes in Maa that are always [+ATR], and other morphemes that display both [+ATR] and [–ATR] allomorphs; but there are no morphemes that always and only have a [–ATR] value unless they never combine with a [+ATR] morpheme. For example, the adjectival form /kìtí/ 'small, little, young' (plural /kʊ̀títꜜí(k)/) is not known to take any prefixes or suffixes which are lexically [+ATR].

The domain of ATR harmony is the phonological word, including clitics. As [+ATR] is phonologically dominant, it may spread toward the beginning of the word (Leftward) from a suffix onto a root or from a root onto a prefix, or it may spread toward the end of the word (Rightward) from a root onto a suffix. In Maa the [+ATR] feature never spreads Rightward from a prefix onto a root, as there are simply no lexical [+ATR] prefixes.

Examples of [+ATR] spreading are given in Table 1 (in examples numbered from (1) to (8)). First, consider examples (1) and (2), in which no morphemes have a [+ATR] value. Examples (3) and (4) show the same roots and some of the same prefixes as in (1) and (2), but this time with lexically [+ATR] suffixes. The [+ATR] value of the suffixes forces a change in the ATR value of the roots plus any prefixes other than those which contain /ɑ/. Example (5) contains a [+ATR] root. However, all the affixes are the same as in examples (1) and (2). The surface [+ATR] form of all the morphemes now shows the dominant effect of the [+ATR] root vowel on both suffixes and prefixes.

Though Maa is a [+ATR] dominant language, as with nine-vowel ATR systems generally /ɑ/ is opaque. This means that *all* morphemes within a word (including clitics) will have [+ATR] vowels if *any* morpheme within the word is lexically [+ATR], just as long as /ɑ/ does not intervene. The vowels /ɑ/ is "opaque" in the sense that it can block further spreading of the [+ATR] feature across it. The term "opaque" is sometimes used to describe a vowel that not only blocks further spreading, but also imposes its ATR feature value on subsequent vowels (cf. Gussenhoven & Jacobs, 1998). However, as will be shortly made clear, Maa /ɑ/ does not impose its [–ATR] feature on surrounding vowels. To see this, compare examples (4) and (6). The Instrumental suffix in (4) is lexically [+ATR]. This causes the [+ATR] feature to surface on all morphemes preceding it. Example (6) contains the same Instrumental suffix. This time, however, the [+ATR] feature is blocked from appearing on the root or any preceding prefixes, because the intervening Away directional morpheme contains /ɑ/. Such data argue that/ɑ/ must be opaque to Leftward spreading.

Table 1
Examples of [+ATR] spreading in Maa words

No morphemes have [+ATR] values		
(1) ɑ́-dɔ́	1SG-be.red	'I am red'
ɑ́-jtɔ́-dꜝɔ́r	1SG-CAUS-be.red	'I will make it red'
ɑ́-tɔ́-dɔ́r-ɔ̀	1SG-PF-be.red-PF	'I have become red'
(2) ɑ́ɑ̀-bɛ̀l-ʊ́ (ɔ̀l-ɑ̀lɑ̂j)	3 > 1SG-break-VENTIVE	'He will knock (my tooth) out'
ɑ́ɑ̀-jtɛ̀-bɛ́l	3 > 1SG-CAUS-break	'He will make me break it'
ɛ̀-tɛ́-bɛ́l-ꜝɑ́	3-PF-break-PF	'He/she broke it'
[+ATR] of suffix spreads to root		
(3) ɑ́-dór-ù	1SG-be.red-INCEP	'I will become red'
(4) é-té-bél-íé	3-PF-break-INST.PF	'He/she used it to break it'
[+ATR] of root spreads to affixes		
(5) ɑ́-pír	1SG-be.fat	'I am fat'
ɑ́-jtó-pìr	1SG-CAUS-be.fat	'I will make it fat'
ɑ́-tó-pír-ò	1SG-PF-be.fat-PF	'I became fat'
[+ATR] of suffix does not spread to root due to blocking /ɑ/		
(6) ɛ̀-tɛ̀-bɛ̀l-ɑ́r-ꜝíé	3-PF-break-AWAY-INST	'He used it to break them (one at a time)'
[+ATR] root with the [+ATR] /or/ allomorph of AWAY and spreading to passive suffix		
(7) è-bòl-ór-ꜝí	3-open-AWAY-PASS	'It will be opened out'
[−ATR] root with [−ATR] passive suffix		
(8) ɑ́ɑ̀-jtɔ̀-dɔ̀r-ɑ̀k-í	3 > 1SG-CAUS-be.red-PF-PASS	'I was made red'

Notes: The vowels /i e o u/ are [+ATR], the rest are [−ATR]. An acute accent (e.g., é) indicates a high tone, a grave accent (e.g. è) a low tone, a circumflex accent a falling tone (e.g., ê), and a superscript exclamation point and acute accent (e.g., ꜝé) a downstepped high tone. Abbreviations are: CAUS, causative; INCEP, inceptive; INST, instrumental applicative; PASS, passive; PF, perfect/perfective aspect; SG, Singular; 3 > 1SG, third person subject and first person singular object.

Thus, in a sense the vowel /ɑ/ is "neutral" because it can occur contiguously with vowels of either the [+ATR] or the [−ATR] sets. Although phonemic /ɑ/ can co-occur with vowels of either set, there is morphological evidence that it patterns with the [−ATR] vowels. For a case in point, compare examples (6) and (7). In (6) there is a [−ATR] root that co-occurs with the /ɑr/ allomorph of the Away directional. In contrast, (7) contains a [+ATR] root which perforce co-occors with the [+ATR] /or/ allomorph of the Away directional. This shows that /ɑ/ patterns as part of the [−ATR] set (see Fig. 1).

There are some differences in the details of the Leftwards vs. Rightwards phonological spreading processes, which we will not pursue in detail here. Suffice it to say that /ɑ/ is opaque to Leftward [+ATR] spreading as seen in (6) but it is not opaque to Rightward [+ATR] spreading. This is shown in (7) where not only do we find [+ATR] /o/, but the [+ATR] feature is further spread to the Passive morpheme. The fact that the AWAY morpheme is not opaque to ATR spreading in (7) above is shown by the fact that the Passive alternatively can take the [−ATR] form /í/ which it clearly does in [–ATR] contexts, as shown in example (8).

1.4. Phonetics of ATR systems

1.4.1. Articulation

Physiologically, it is generally agreed that ATR contrasts correspond to differences in the size of the pharyngeal cavity. The [+ATR] configurations have a larger pharyngeal cavity and the [−ATR] configurations have a smaller cavity. However, it seems that articulatory investigation into the ATR contrast has been greater for Niger-Congo than Nilo-Saharan languages. In an early study on Igbo, a Niger-Congo language spoken in Nigeria, Ladefoged (1968) reported data from X-ray cinematography in which the primary difference in the ATR vowel pairs was found to be tongue root retraction. Lindau (1974, 1979) then presented X-ray data for Akan, a Niger-Congo language of Ghana, indicating that changes in size of the pharyngeal cavity can be accomplished not only by retraction or advancement of the tongue root but also by raising or lowering the larynx. Recent magnetic resonance imaging on Akan presented by Tiede (1996) indicates that the pharyngeal expansion is accomplished not only in the sagittal direction (by tongue root advancement) but also in the transverse direction. Thus the [+ATR] configuration in Akan is affected by an overall expansion of the pharynx in sagittal and transverse directions in addition to the lowering of the larynx. Tiede (1996) also found that the [−ATR] vowels in Akan were produced with pharyngeal sagittal and transverse constriction in addition to larynx raising.

Jacobson (1978, 1980) appears to be the main source for articulatory data on the production of vowels in Nilo-Saharan languages. He reports on still X-ray tracings of the midsaggital section for the production of ATR vowel pairs for DhoLuo of Kenya, Shilluk (Sudan), and Dinka (Sudan). The pharyngeal cavity was generally larger for the [+ATR] vowels. However, the method for cavity expansion was not uniform across the three languages. Specifically, laryngeal raising was not found for all contrasts in all languages.

No articulatory data on vowel production could be readily found in the literature on Maa. In the absence of such data we can only cautiously assume that mechanisms similar to those described for the Niger-Congo and Nilotic languages previously investigated are used in Maa. The current study does not directly address the gestural physiology of the tongue root or pharyngeal cavity.

Another production characteristic potentially associated with ATR contrasts is voice quality. In general, vowels produced with an expanded pharynx are often associated with a more lax or breathy voice quality. Descriptions of Akan dialects report [+ATR] vowels to be relatively more 'breathy', 'full' or 'deep' than the [−ATR] vowels (Berry, 1955; Stewart, 1967). In the case of Maa, Tucker and Mpaayei (1955) have described the [+ATR] vowels as having a "somewhat 'breathy' voice quality" (p. 51). Author DLP has approximately 10 years of experience with Maa, and does sometimes detect slight voice quality differences, but not in all cases, and hears no clear difference in the data recorded for the current study. She finds a clear difference between the slight to inaudible voice quality distinction in Maa and the salient voice quality distinctions in other Nilotic languages such as Saboat and Endo (both Southern Nilotic). Authors SGG and MWP also hear no clear voice quality distinctions in the data.

It seems that all previous reports of voice quality associates of ATR distinctions have been based on auditory or acoustic data and that physiological investigation (using, e.g., electroglottography) has not been reported in the literature for any ATR language.

1.4.2. Acoustics

The manipulation of the overall size of the pharyngeal cavity in ATR contrasts is expected to have several acoustic consequences. First, the larger size of the pharyngeal cavity will produce a lower resonant frequency for the first formant (F1) (Halle & Stevens, 1969). This is, in fact, the most reliable and established acoustic correlate to the ATR contrast (see e.g., Lindau, 1978; Hess, 1992 for Akan; Jacobson, 1980 for Nilotic languages; and Fulop, Kari & Ladefoged, 1998 for Degema, a Niger-Congo language spoken in Nigeria). A preliminary investigation of the formant values in Maa by Bush (1999) showed a lower F1 for most [+ATR] vowels.

The second formant (F2) has also been found, in some cases, to vary systematically across the ATR vowel sets. This variation, however, does not seem to be consistent from language to language. For some languages, differences in F2 across the ATR vowel pairs is characterized by [−ATR] vowels tending to more peripheral F2 values. Namely, the [−ATR] front vowels have greater F2 values and the [−ATR] back vowels have smaller F2 values than the corresponding [+ATR] vowels. Jacobson (1980) noted such F2 effects for only some of the vowel pairs in the Nilotic languages DhoLuo and Shilluk and not at all for Dinka. On the other hand, the F2 values for the [+ATR] vowels were consistently found to have more peripheral values in the Niger-Congo language Degema reported by Fulop et al. (1998). Thus, it is unclear whether there is any systematic cross-linguistic relationship between ATR and F2.

Another acoustic correlate of the ATR contrast is the difference in spectral slope between [+ATR] and [–ATR] vowels. As mentioned above, [+ATR] vowels are often heard as more “deep”, “hollow”, or “breathy”. In addition [−ATR] vowels are sometimes described as “brighter”, “brassy” or “creaky” (Berry, 1955; Stewart, 1967; Jacobson, 1980). These auditory impressions have been shown to be related to the overall slope of the spectrum. Using a procedure that normalized the effect of vocal tract resonances on the spectral slope, Fulop et al. (1998) reported that higher frequency energy is a relatively greater contributor to the spectra of [−ATR] than [+ATR] vowels in Degema (but see Ladefoged & Maddieson, 1996, p. 302). Similar findings were reported for Akan by Hess (1992) who found that [−ATR] vowels had lower F1 amplitudes (as evidenced by greater F1 bandwidths) than [+ATR] vowels. Hess used no normalization procedure but, instead, compared Akan vowels of similar formant structure. Namely, the bandwidths of high [–ATR] vowels /ɪ/ and /ʊ/ were compared to those of the mid [+ATR] vowels/e/and/o/.

Thus, it seems that for the Niger-Congo languages examined, the [+ATR] vowels have relatively more low frequency energy, whereas the [−ATR] vowels have relatively more high frequency energy. That is, the slope of the spectrum falls off more steeply in [+ATR] than [−ATR] vowels.

There are several possible articulatory origins for the spectral correlates of the ATR contrast. First, they could be the result of voice quality differences. The source spectrum for breathy phonation is associated with less harmonic energy in the high-frequency range than modal phonation due to the more sinusoidal nature of the vocal fold vibration during breathy voicing (see, e.g., Stevens, 1998, pp. 85–92). Stevens (p. 89) reports that spectra of vowels produced with breathy voicing can have an amplitude reduction of as much as 15 dB in the higher frequencies as compared to modal vowels. The first harmonic is about the same for the two phonation types. Thus, breathy vowels have a much steeper spectral slope than modal vowels. If [+ATR] vowels are indeed produced with more lax or breathy voicing, then this fact could at least partially explain the relatively diminished high-frequency energy observed.

Another possible origin for spectral slope differences could be found in the muscular tension of the pharyngeal walls. Greater tension, and thus stiffness, of the pharyngeal walls would produce less damping (i.e., less dissipation of acoustic energy) than a relatively laxer configuration. However, it is unclear whether greater muscular tension is more likely to occur in the [+ATR] or the [−ATR] vowels (Tiede, 1996; Fulop et al., 1998).

A third possible contributor to differences in spectral slope is the effect of pharyngeal constriction on the amplitude of the first formant. A tightly constricted pharynx in a [−ATR] vowel can produce friction damping in the frequency range of F1 due to the viscosity of the air (see Fulop et al., 1998 for discussion).

1.5. The current study

The analyses presented here are designed to make two types of comparisons. First, the effect of ATR for vowel pairs that pattern together phonologically will be investigated. The [±ATR] pairs of /i, ɪ/, /e, ɛ/, /o, ɔ/, /u, ʊ/ will be compared as well as the low vowel /a/ in both [+ATR] and [−ATR] contexts. The second type of comparison is concerned with differences between the [−ATR] high vowels and the [+ATR] mid vowels, namely the contrasts of /ɪ, e/ and /ʊ, o/. These comparisons are of interest due to the auditory similarity between these vowels, as well as their similarity in formant structure.

The points of comparison used in the analysis are (1) first formant frequency, (2) second formant frequency, (3) duration, (4) relative spectral slope, and (5) electroglottography. The data for the first four measures were collected from five speakers and the data for the last measure were collected from a single speaker.

2. Method

2.1. Speakers

Data for this paper were collected from five Maa-English bilingual male speakers, all of whom grew up in southern Kenya, from the Kajiado region (south of Nairobi), the Narok region (on the western side of the Rift Valley), and the Kilgoris region.

Speaker LK belongs to the il-Keekonyokie section, and grew up in the Narok region close to Suswa. He attended rural (non-boarding) primary and secondary schools close to his home area, and completed university studies in Nairobi. The majority of his schooling (especially secondary and university studies) has been in English. He has taken courses in linguistics in Nairobi, including phonetics. Though he has lived primarily in Nairobi since the time of his university studies, he travels frequently to his home area. Several years prior to the time that data was collected for this study, LK spent about 2 months in the western United States. LK has mastered the transcription of tone and ATR distinctions in Maa, and has worked for about 8 years with author DLP on a Maa language project. LK has some familiarity with varieties of Maa spoken in the Samburu and Laikipia (northern Kenya) regions, as well as with Kisonko Maa spoken south of Arusha.

KM and MS belong to the il-Purko section, both having grown up in the Kajiado region of Southern Kenya. KM attended rural boarding school for primary and secondary education, and completed university studies in Nairobi. MS has completed secondary school. Again, secondary and university studies have been in English. Both KM and MS travel frequently in the rural Maa area, though KM has spent comparatively more time in the Nairobi metropolitan area. KM has also mastered the transcription of tone and ATR distinctions in his own language, and has worked for several years on the Maa language project. Neither KM nor MS have traveled outside of East Africa.

KN and VK belong to the il-Wuasinkishu section of southwestern Kenya. Dialect differences from the more centrally located il-Keekonyokie and il-Purko regions include relatively minor vocabulary differences, and some different properties of at least one known syntactic construction. KN and VK come from the same village, and completed their primary and secondary studies at the same Maa-Swahili-English schools in western Kenya. KN then undertook university studies in the western United States; data for this study were collected while he was a university student in the United States. VK completed his university studies in India, and then returned to Kenya. He later began postbaccalaureate studies at a university in the western United States; data for this study were collected while he was a student at this university.

2.2. Materials and recording

Speakers were asked to read words from a large prepared wordlist exemplifying [+ATR] and [−ATR] variants of all four ATR vowel contrasts (/i,ɪ/, /e, ɛ/, /o,ɔ/, /u,ʊ/), as well as /ɑ/ in [+ATR] and [−ATR] contexts. Speakers read an alphanumeric designator (e.g., A1) for the word and then said the word three times. The words were presented in standard Swahili orthography, with which the speakers were familiar, and which does not represent tone or ATR distinctions. A subset of 100 words, with 10 words exemplifying each of the vowels under investigation, was selected for analysis in the current study (see Appendix A). Thus, 1500 words were analyzed (10 vowel types × 10 words × 3 repetitions × 5 speakers). Although true minimal pairs are typically unavailable in Maa, we were able to obtain near-minimal ATR pairs for which tone, surrounding consonant manner/voicing, and in most cases consonant place and syllable position within the word, were constant.

Speakers MS, KN, LK and KM were recorded in the field (MS, LK and KM in Kenya and KN in the US) using a Marantz PMD 222 tape recorder; speaker VK was recorded in the Phonetics Lab at the University of Oregon on a Tascam DA-P1 digital audio tape (DAT) recorder. All speakers were recorded using a unidirectional, head-mounted microphone (Shure SM10A). The analog recordings were digitized (22,050 Hz sampling rate) using a Kay Elemetrics CSL 4400. The DAT recordings were digitally transferred to a computer using the CSL 4400 and then down sampled to 22,050 Hz to allow the same analysis parameters to be used for all speakers.

Electroglottographic (EGG) data for the 100 test words was also obtained from speaker VK using Kay Elemetrics EGG hardware 6103 and the CSL 4400. He was recorded reading the list of words in Appendix A in the same fashion described above while wearing a collar holding electrodes on either side of his larynx for the EGG recording and the head-mounted microphone for a simultaneous audio recording on a separate channel.

2.3. *Analysis*

2.3.1. *Formant frequencies*

First, second, and third formant frequencies were measured at the temporal midpoint of the vowel using Scicon PCquirer acoustic analysis software. Both FFT (512 points) and LPC (26 coefficients) spectra were calculated and plotted in a single window. The peaks from the formant-picking algorithm based on the LPC analysis were recorded except in the very few instances in which the LPC peaks did not align with the FFT spectral peaks on visual inspection. In these cases, the spectra were recalculated 5–10 ms later or earlier in the waveform and if the spectral peaks aligned, the LPC peaks were recorded. In the small number of cases ($<1\%$) where LPC formant readings could not be reconciled with the harmonics from the narrowband FFT spectra, wideband FFT (128 points) spectra were recalculated and the formant frequency was measured by hand from these spectra.

An inspection of the values for the three repetitions of the F1 and F2 frequency measures revealed very little difference across the three productions. Because there were no experimental hypothesis concerning repetition and because there was little variation across the three repetitions, mean values were used in all formant analyses reported below. Individual repetitions of the F1, F2 and F3 measures were used in the amplitude normalization procedure described below.

2.3.2. *Spectral slope*

In order to determine whether the spectral slope between [+ATR] and [−ATR] vowels differed in Maa, the difference in relative first and second formant intensity was calculated for the ATR vowel pairs under investigation. It was not possible to directly compare the spectral slope or bandwidth for the vowel pairs of primary interest in this study, i.e. phonologically related [+ATR] and [−ATR] vowels (e.g., [e] and [ɛ] because the frequency of the formants (esp. F1) are known to vary as a function of [ATR] status. This is a problem for a direct comparison because amplitude and bandwidth vary as a function of formant frequency due to properties of the vocal tract (Fant, 1960). In addition, as formants vary in their proximity to one another, they affect the amplitude of one another: The closer they are to one another, the greater mutual reinforcement they will have. Thus, a normalizing procedure was needed to allow a comparison of the relative spectral slopes of vowels with different formant frequencies.

Normalizing procedures have been used for spectral slope measures involving the first harmonic (H1) (see Hanson, 1997, 1999). However, procedures involving H1 are only viable when the first formant is relatively high (as in mid and low vowels). In the current investigation, high vowels (i.e., vowels with a low first formant) were to be considered as well as mid and low vowels, so a normalizing procedure using the amplitudes of the first and second formants (A1 and A2) was more suitable. Here, the normalization procedure for A1–A2 developed by Fulop et al. (1998) to investigate phonetic properties of ATR contrasts in Degema was used. This method provides a baseline relative amplitude for the first and second formants, for any given vowel, that measured A1–A2 data can be set against. Thus, the relative difference between the baseline and measured data for [+ATR] and [−ATR] vowels can be compared. Fulop et al. (1998) have argued that differences in relative formant intensity indicate differences in ATR.

In the current study, the amplitude of the first two formants was approximated using the same spectral analysis and display used for the formant measurements. The amplitude, in decibels, of the most prominent harmonic from the narrowband FFT spectrum that was found to be clearly within the formant band defined by the LPC tracing was measured. These measures only approximate the amplitudes of the first and second formant, as the most prominent harmonic may or may not be at the central frequency of the resonance.

Then, using the procedure of Fulop et al. (1998), the baseline or modeled amplitudes for the measured F1 and F2 frequencies were determined by calculating the expected formant amplitudes of a vocal tract model with constant source and resonance characteristics. The modeled A2 was subtracted from the modeled A1. These values (modeled A1–A2) were then subtracted from the measured A1–A2 values. If the difference between the modeled and measured A1–A2 values differed by ATR status, then it could be it attributed to source or resonance characteristics that correlated with the ATR configuration.

The modeled A1 and A2 values were calculated using the method published in Fulop et al. (1998, pp. 89–90), reproduced here for convenience. For each A1 and A2 value to be modeled, the following was done. First, the modeled contribution (in dB) of F1 at the frequency of the measured formant, f, was calculated using the formula in (1). Then, using the formula in (1) again, the relative contributions of F2 and F3 at the same measured frequency, f, were calculated. The modeled contributions of F1, F2 and F3 were then summed. Then, the modeled contributions of the higher formants (i.e., above F3) to the amplitude at the frequency of the measured formant, f, were added as determined by Eq. (2). Finally, the modeled effects of radiation at the mouth as well as the glottal pulse shape to the amplitude at the frequency of the measured formant, f, were added by the equation in (3). Eq. (3) assumed a modal-like voicing ($g = 1$), so the combined effects of the source spectrum and radiation characteristics contributed a negative spectral slope falling at a rate of 6 dB per octave.

$$dB(f) = 20\log_{10}\frac{F^2 + (b/2)^2}{\sqrt{(f-F)^2 + (b/2)^2} \times \sqrt{(f+F)^2 + (b/2)^2}}, \tag{1}$$

where F is the measured resonant frequency (F1, F3 or F3) and b is the bandwidth of the resonance (30 Hz for F1, 80 Hz for F2 and 150 Hz for F3).

$$dB(f) = 0.72(f/492)^2 + 0.0033(f/492)^4, \tag{2}$$

$$dB(f) = g\left(-20\log_{10}\left(2\frac{f/100}{1 + (f/100)^2}\right)\right), \tag{3}$$

where g is a variable representing phonation type; here set to 1.0.

The modeled A1 and A2 values were calculated for each repetition of each word. Then, the difference between the observed A1–A2 and modeled A1–A2 was calculated, producing a measure of the normalized relative intensity of the first to the second formant. This measure will be called normalized A1–A2 here and will be used in analyses investigating spectral slope difference for the

[+ATR] and [−ATR] vowel types. As the A2 was of lesser intensity than the A1 for all the measured and modeled data, all A1–A2 values were positive. Thus, differences between the observed A1–A2 and modeled A1–A2 can be directly interpreted as differences in steepness of spectral slope.

2.3.3. Duration

The duration of each vowel was also measured in order to determine whether the ATR contrast had any temporal effects. The measures were made using waveform and spectrographic displays in PCquirer. The duration of the vowel was measured from the onset of the first full glottal pulse to the offset of the last full glottal pulse corresponding with visible second formant energy in the spectrogram. As little variation in duration was observed for the three repetitions of each word, mean values were used in the statistical analyses.

2.3.4. Electroglottography

The EGG waveforms from speaker VK were investigated in order to estimate the percentage or quotient of the glottal cycle in which the glottis was closed. Greater glottal constriction leads to more glottal contact across the vibratory cycle. Conversely, more lax or breathy phonation is associated with a less tightly closed glottis, producing a relatively greater open portion of the cycle than modal, tense, or creaky voicing (see, e.g., Ladefoged & Maddieson, 1996).

The ratio of the contact portion to the duration of the entire cycle is called the contact quotient and indicates the relative amount of glottal contact during phonation (see, e.g., Orlikoff 1991). Higher ratios indicate relatively more contact and lower ratios indicate relatively less contact. Thus, differences in the contact quotient (CQ) for the [±ATR] vowels under investigation here could indicate differences in phonation type. A lower CQ would indicate a relatively less constricted glottis and relatively more lax or breathy phonation.

The measurements for calculating the CQ were taken from the glottal cycle closest to the temporal midpoint of the vowel using the Kay Elemetrics CSL software. The measurements made were (1) the duration of the contact portion and (2) the duration of the complete glottal cycle.

The onset of the contact portion was determined visually as an upward moving "deflection point" as follows: The EGG waveform plots the impedance of the current being passed across the glottis: As the glottis closes, the impedance is reduced. This is plotted as upward movement. This upward movement was visually inspected and the location of the greatest change in increase of the slope was considered as the onset of the contact portion of the cycle (see Orlikoff, 1991). The end of the contact portion was determined by locating the same impedance value on the downward slope. The duration between these two points was then recorded as an estimate of the contact portion. The duration of the complete glottal cycle was measured as the duration from deflection point to deflection point, that is from the contact onset of the glottal cycle under inspection to the contact onset of the subsequent glottal cycle. See Fig. 2 for an example of the measurement points.

The CQ was calculated as the ratio of the contact portion to the entire glottal cycle. Measures were made for each of the three repetitions of the 100 words. Inspection of the three repetitions revealed very little variance in the CQ values for each word, thus, mean values across three repetitions were used in the statistical analyses.

Reliability of the measurement was assessed by remeasuring a subset of the data. Four words were randomly chosen from each of the ten vowel types, for a total of 40 tokens. Author MWP

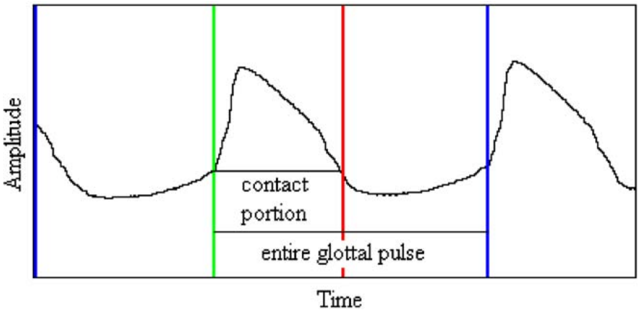

Fig. 2. Example locations for the measurement of contact portion and entire glottal cycle used in the calculation of the contact quotient (CQ) from the EGG waveform.

(who first measured all 100 words) remeasured the first repetition of the 40 words under consideration after a time span of 4 months. Author SGG also measured the first repetition of the 40 words. The CQ for each word was then calculated and submitted to an intraclass correlation analysis. The intraclass correlation coefficient (MacGraw & Wong, 1996) for the two ratings done by MWP was quite high ($\rho = 0.97$, $p < 0.001$). This indicates that the rater was able to consistently locate "deflection points" with a high degree of reliability. When the first rating by MWP and the rating by SGG were submitted to a single measure intraclass correlation (which indicates the reliability when a single rater is used, as was the case here), the correlation coefficient was also high ($\rho = 0.95$, $p < 0.001$), indicating that the use of one rater was highly reliable.

3. Results

3.1. Formant values

In this section, the results of statistical tests designed to determine whether ATR vowel pairs differ in formant values (F1 and F2) are presented. Recall that five speakers produced 10 words exemplifying each of the 10 vowel categories three times each.

First consider the formant values plotted in Fig. 3. Note that in general the [+ATR] vowels have lower F1 values than their [−ATR] counterparts for all but the low vowels. In addition, for the front vowels, the [+ATR] vowels tend to have greater F2 values than their [−ATR] counterparts for some speakers. It is also noteworthy that, for several speakers, the [−ATR] high vowels /ɪ/ and /ʊ/, tend to have very similar formant structure to the [+ATR] vowels /e/ and /o/ respectively.

First, the F1 values of the vowels from the ATR word pairs were submitted to a mixed design ANOVA with three factors: Vowel Quality (5:/i,ɪ/, /e,ɛ/, /o,ɔ/, /u,ʊ/, and /a/ in [+ATR] and [−ATR] contexts), Speaker (5: VK, MS, KM, LK, KN), and ATR value ([+ATR] vs. [−ATR]). The last two factors were treated as repeated measures. The alpha-value for significance is set at 0.05 throughout the results section.

The main effect of ATR was significant [$F(1,45) = 196.80$, $p < 0.001$], with the [+ATR] vowels having lower F1 values than the [−ATR] vowels. ATR interacted with Vowel Quality

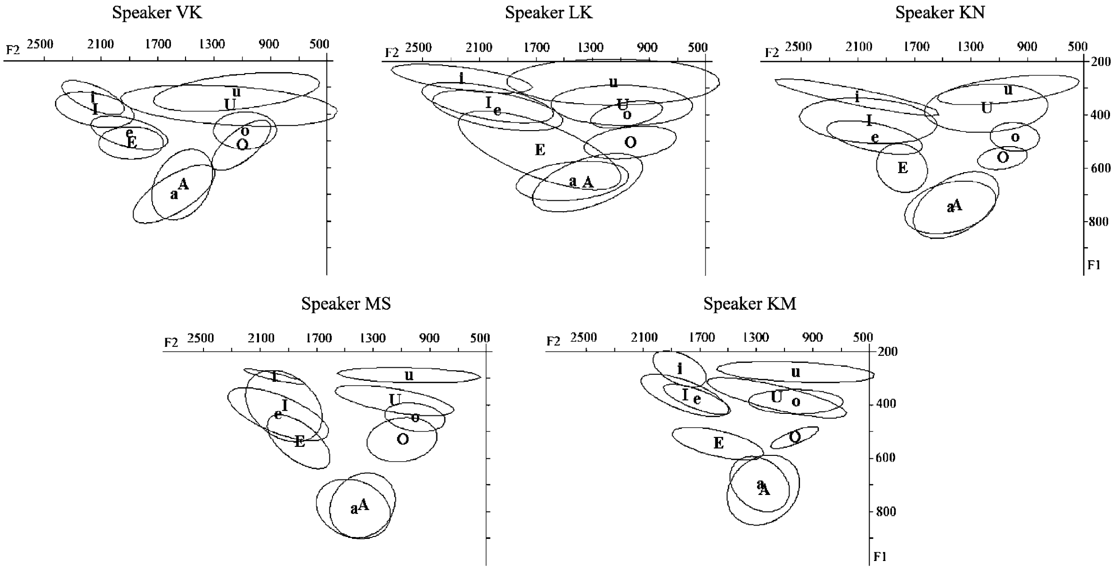

Fig. 3. First formant (F1) over second formant (F2) values from the vowel productions of five Maa speakers. The position of the vowel label indicates the mean value and the ellipses enclose +/−2 standard deviations, rotated along the axis of the first principal component to reflect the correlation between the formants. The [+ATR] vowels (and /ɑ/ in a [+ATR] context) are indicated with lower case labels. The [−ATR] vowels (and /ɑ/ in a [−ATR] context) are indicated with the upper case labels.

[$F(4,45) = 15.30$, $p < 0.001$] but the three-way interaction with Vowel Quality and Speaker was not significant [$F(16,180) = 1.36$]. These results indicate that there are differences in the F1 of [±ATR] vowels for at least some of the vowel pairs and that the effect is consistent across the speakers.

To further investigate the effect of ATR on the F1 of the vowel pairs, five separate ANOVAs on the F1 values were conducted, one for each vowel quality, with the factors of ATR and Speaker (significance level adjusted to 0.01 for 5 comparisons). The main effect of ATR is of primary interest here, since the three-way interaction of the overall ANOVA was non-significant. In the case of the low vowels (/ɑ/ in a [+ATR] context and /ɑ/ in a [−ATR] context), the effect of ATR was not significant [$F(1,9) = 0.13$]. This indicates that /ɑ/ does not differ in terms of F1 between [+ATR] and [−ATR] contexts. For the other vowel pairs, /e,ɛ/, /i,ɪ/, /o,ɔ/ and /u,ʊ/, the effect of ATR was significant in all cases [$F(1,9) = 57.03$, $F(1,9) = 147.58$, $F(1,9) = 107.84$, and $F(1,9) = 70.99$, all $p < 0.001$]. This indicates that the [+ATR] mid and high vowels all have significantly lower F1 values than their [−ATR] counterparts.

The F2 values for the ATR vowel pairs were subjected to the same type of analysis as the F1 values. First, an overall mixed design ANOVA with the factors of Vowel Quality (5), Speaker (5, repeated measures), and ATR value ([+ATR] vs. [−ATR], repeated measures) was conducted. The main effect of ATR was not significant [$F(1,45) = 2.24$] but the interaction of ATR and Vowel Quality was [$F(4,45) = 3.04$, $p = 0.027$]. The three-way interaction of ATR with Vowel Quality and Speaker was not significant [$F(16,180) = 1.33$]. These results indicate that there may be differences in the F2 of [±ATR] vowels, for at least some of the vowel pairs, and that the effect of ATR on the vowel pairs is consistent across the speakers.

To further investigate these results, five separate ANOVAs on the F2 values were conducted, one for each vowel quality, with the factors of ATR and Speaker (significance level adjusted to 0.01 for 5 comparisons). Once again, the main effect of ATR is of primary interest, since the three-way interaction of the overall ANOVA was non-significant. As was the case for the F1 values, the effect of ATR was not significant for the low vowels (/ɑ/ in a [+ATR] context and /ɑ/ in a [−ATR] context), [$F(1,9)=0.78$]. This indicates that /ɑ/ does not differ in terms of F2 between [+ATR] and [−ATR] contexts. The effect of ATR was also not significant for the back vowel pairs /o,ɔ/ and /u,ʊ/ [$F(1,9)=1.24$ and $F(1,9)=1.82$]. The front vowels showed a trend for higher F2 values for the [+ATR] member of the pair, especially for speakers LK and KN (see Fig. 3). However, the main effect of ATR on F2 was not significant for the /e,ɛ/ and /i,ɪ/ comparisons [$F(1,9)=5.59$ and $F(1,9)=4.99$]. These results indicate that the [±ATR] vowel pairs are not reliably distinguished by F2.

Given the phonetic similarity of [–ATR] /ɪ/ to [+ATR] /e/ and [–ATR] /ʊ/ to [+ATR] /o/, the formant values for these vowels were also investigated. First, /ɪ/ and /e/ were considered. The F1 values for [−ATR] /ɪ/ and [+ATR] /e/ were investigated in an ANOVA with the factors of Vowel (2) and Speaker (5), with repeated measures on the last factor. The factor of Vowel was treated as a between subjects factor here since the words were not matched for phonetic context. The overall effect of Vowel was found to be significant [$F(1,18)=15.34$, $p<0.001$], as well as the interaction with Speaker [$F(4,72)=2.71$, $p=0.037$]. This indicates that speakers differed with respect to the frequencies of F1 between /ɪ/ and /e/. Five separate one-way ANOVAs, one for each speaker, with the factor of Vowel were conducted to further explore the interaction (significance level adjusted to 0.01 for 5 comparisons). The vowels /ɪ/ and /e/ were found to differ in F1 (with /ɪ/ having a lower value) for speakers VK and KN [$F(1,18)=32.64$, $p<0.001$, $F(1,18)=12.26$, $p=0.003$], but not for speakers MS, KM or LK [$F(1,18)=1.22$, $F(1,18)=0.76$, $F(1,18)=2.71$]. Note that speakers VK and KN are from the same dialect area.

The F2 values for [–ATR] /ɪ/ and [+ATR] /e/ were investigated with an ANOVA having the factors Vowel (2) and Speaker (5), with repeated measures on the last factor. The effect of Vowel was not significant [$F(1,18)=1.53$], but the interaction with Speaker was [$F(4,72)=3.15$, $\rho=0.019$]. To investigate the interaction, five separate one-way ANOVAs, one for each speaker, with the factor of vowel were conducted (significance level adjusted to 0.01 for 5 comparisons). The vowels /ɪ/ and /e/ differed in terms of F2 (with /ɪ/ having a higher value) only for speaker VK [$F(1,18)=14.30$, $p<0.001$]. The other four speakers showed no significant difference in the F2 values for these vowels [F-values range from 0.21 to 1.87].

The F1 and F2 values for the vowels /ʊ/ and /o/ were considered next. The F1 values were investigated with a two-way ANOVA having the factors of Speaker (5) and Vowel (2). The overall effect of Vowel was found to be significant [$F(1,18)=36.64$, $p<0.001$], as well as the interaction with Speaker [$F(4,72)=8.98$, $p<0.001$]. Individual ANOVAs testing the effect of Vowel on each of the five speakers revealed that speakers VK, MS, and KN had significantly greater F1 values for /o/ than for /ʊ/ [$F(1,18)=28.88$, $F(1,18)=23.17$, $F(1,18)=37.46$, all $p<0.001$]. Speakers KM and LK, on the other hand, did not produce significantly different F1's for the two vowels [$F(1,18)=1.01$ and $F(1,18)=4.33$].

An investigation of the F2 values for the vowels /ʊ/ and /o/ did not reveal any significant results. The main effect of vowel was not significant [$F(1,18) = 2.08$], nor was the interaction with speaker [$F(4,72) = 1.33$]. This indicates that /ʊ/ and /o/ are not differentiated by F2 for any of the speakers.

3.2. Duration

First, the results of a statistical test designed to determine whether [±ATR] vowel pairs differ in duration is presented. A mixed design ANOVA with three factors, Vowel Quality (5: /i,ɪ/, /e,ɛ/, /o,ɔ/, /u,ʊ/, and /ɑ/ [+ATR] context, /ɑ/ [–ATR] context), Speaker (5: VK, MS, KM, LK, KN), and ATR value ([+ATR] vs. [−ATR]), was conducted. The factors of Speaker and ATR were treated as repeated measures. The overall effect of ATR was not significant [$F(1,45) = 0.12$], nor were the interaction of ATR and Vowel Quality [$F(4,45) = 0.98$], and the interaction of ATR, Vowel Quality and Speaker [$F(16,180) = 0.96$]. These results indicate that [±ATR] vowel pairs do not differ in duration for any of the vowel qualities, for any of the speakers.

Given the spectral similarity of [−ATR] /ɪ/ to [+ATR] /e/ and [−ATR] /ʊ/ to [+ATR] /o/, the durations for these vowels were also considered to determine if the vowels differed temporally. A two-way ANOVA with the factors of Speaker (5) and Vowel (2) was first applied to durational values of [ɪ] and [e]. The factor of vowel was treated as between subjects because the words for these vowels were not paired for phonetic context. The overall effect of Vowel was found to be non-significant [$F(1,18) = 0.73$], but the interaction with Speaker was significant [$F(4,72) = 2.75$, $p = 0.035$]. However, individual ANOVAs testing the effect of Vowel on each of the five speakers revealed that none of the speakers produced a significant difference in vowel length [F-values range from 0.01 to 5.35] (significance level adjusted to 0.01 for 5 comparisons).

The duration of the [−ATR] /ʊ/ was compared with that of the [+ATR] /o/ vowels in a similar ANOVA. The effect of Vowel was significant [$F(1,18) = 18.79$, $p < 0.001$] and the interaction with Speaker was not significant [$F(4,72) = 1.96$]. On average, the [+ATR] /o/ vowels were 105 ms long, where as the [−ATR] /ʊ/ vowels were only 76.96 ms long. All speakers showed this effect. Given the fact that these vowels were not paired for position in the word or for syllabic structure, it is possible that this difference came about due to, for example, more word final lengthening in the [+ATR] /o/ words. An inspection of the words used (found in Appendix A) reveals that this is unlikely, however. The /o/ appeared 3 times initially, 4 times medially, and 3 times in final, closed syllables. The /ʊ/ appeared 8 times medially, and 2 times in final, closed syllables. However, without matched pairs, the finding that /o/ has a greater duration than /ʊ/ may be taken as preliminary until further corroborated.

3.3. Normalized relative formant intensity

The results for normalized relative intensity of the first to the second formant, here called normalized A1–A2, are reported in this section. First, consider Fig. 4, which displays the mean normalized A1–A2 values for each of the vowel types investigated. Note that there is an overall trend for the [+ATR] vowels to have a greater normalized A1–A2 than their [−ATR]

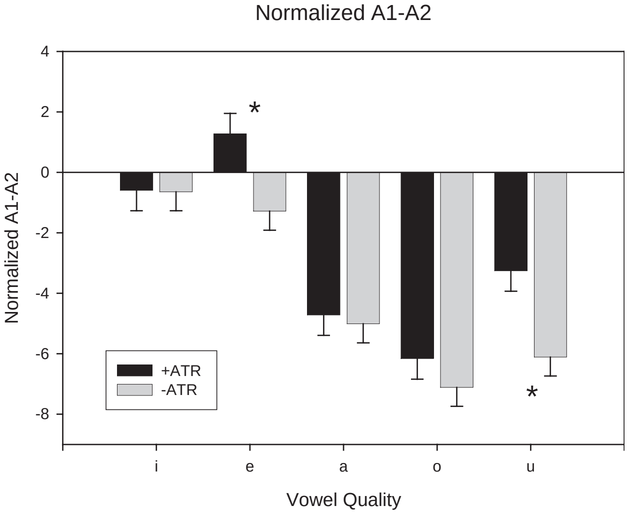

Fig. 4. Mean values with standard errors for the normalized relative intensity of the first to the second formant (normalized A1–A2 calculated by subtracting the Modeled A1–A2 values from the Observed A1–A2 values) for five Maa speakers. Significant differences in ATR for a given vowel quality are marked with an asterisk. Greater values indicate relatively greater spectral slopes for the observed than the modeled values.

counterpart. This indicates that the [+ATR] vowels tend to have relatively greater spectral slopes for the observed than the modeled values than the [−ATR] vowels do.

The normalized A1–A2 for each vowel was submitted to a mixed design ANOVA with the factors of Vowel Quality (5), Speaker (5), Repetition (3) and ATR value (2), with repeated measures on the last three factors. Because normalized relative intensity is a highly derivative measure, the amount of variability for this measure across multiple repetitions of a word was somewhat greater than the other measures. Therefore, Repetition was included as a factor in these analyses instead of using mean values.

The overall effect of ATR was significant [$F(1,45)=15.85$, $p<0.001$], as was the interaction of ATR with Vowel Quality [$F(4,45)=2.96$, $p = 0.03$]. The interaction of ATR with Vowel Quality and Speaker was, however, not significant [$F(16,180)=1.03$]. The main effect of Repetition was not significant [$F(2,90)=0.15$]; neither were the two-, three- or four-way interactions of Repetition with any of the other factors [F-values range from 0.29 to 1.27] These results indicate that the effect of ATR on the normalized A1–A2 values differs by vowel type. However, the five speakers within each vowel type do not tend to differ from each other. Therefore, in the following analyses, we will be primarily concerned with the main effect of ATR on each vowel type.

In further investigation, five separate ANOVAs were performed, one for each vowel type, to explore the effect of ATR (significance level adjusted to 0.01 for 5 comparisons). The factors of Speaker (5), Repetition (5) and ATR (2), all repeated measures, were used. Non-significant effects of ATR were found for /ɑ/ in a [+ATR] vs. [−ATR] context [$F(1,9)=0.17$], the /i,ɪ/ vowel pairs [$F(1,9)=0.002$], and the /o,ɔ/ vowel pairs [$F(1,9)=2.12$]. Significant effects for ATR were found for the /e,ɛ/ vowel pairs [$F(1,9)=11.05$, $p = 0.009$] and the /u,ʊ/ [$F(1,9)=23.87$, $p = 0.001$] vowel pairs. In both of these cases the [+ATR] vowel had a greater normalized A1–A2 than the [−ATR] vowel (1.27 vs. −1.28 for /e,ɛ/ and −3.26 vs. −6.11 for /u,ʊ/), indicating relatively steeper spectral slopes for the observed than the modeled values for the [+ATR] vowels.

Again, given the spectral similarity of the [−ATR] high vowels to the [+ATR] mid vowels, investigation into the Normalized A1–A2 measure was undertaken for /ɪ/ vs. /e/ and /ʊ/ vs. /o/. The results from the /ɪ/ vs. /e/ are presented first. The Normalized A1–A2 values for /ɪ/ and /e/ were submitted to a three-way ANOVA with the factors of Speaker (5), Repetition (3) and Vowel (2), with repeated measures on the first two. The effect of Vowel was significant [$F(1,18)=9.50$, $p=0.008$], as was the interaction with Speaker [$F(4,72)=3.34$, $p=0.014$]. This indicates that at least some speakers had different values for the Normalized A1–A2 across the two vowel types. The interaction was investigated by testing the effect of Vowel for each of the speakers separately. Speakers MS and KM, both from the same dialect area, had significantly greater Normalized A1–A2 values for the [−ATR] /ɪ/ than the [+ATR] /e/ [$F(1,18)=8.12$, $p=0.011$ and $F(1,18)=11.76$, $p=0.003$]. The other talkers did not have significant effects [F-values ranged from 0.08 to 2.33] but did show trends in the same direction.

Investigation into the normalized relative formant intensity of the /ʊ/ and /o/ vowels did not return any significant effects. The effect of Vowel was not significant [$F(1,18)=0.004$], nor was the interaction with Speaker [$F(4,72)=0.72$].

3.4. Electroglottography

The electroglottographic (EGG) data for speaker VK are reported in this section. The ratio of the contact portion to the duration of the vibratory cycle, the closure quotient (CQ), was calculated by measurements taken on the EGG waveform as described in the method section.

First, consider Fig. 5, which displays the mean CQ values for each of the vowel types investigated. Note that there is an overall trend for the [+ATR] vowels to have a smaller CQ values than their [−ATR] counterpart. That is, the [+ATR] vowels tend to be produced with less contact of the vocal folds, indicating a less constricted glottis and, thus, relatively more breathy phonation, than the [−ATR] vowels.

The mean CQ values were submitted to a mixed-design ANOVA with the factors of ATR (2, repeated measures) and Vowel (5). The main effect of ATR was significant [$F(1,45)=4.60$, $p=0.037$]. The [−ATR] vowels had slightly higher CQ values (0.51) than the [+ATR] vowels (0.49). The main effect of vowel [$F(4,45)=6.77$, $p<0.001$] was also significant. The interaction of ATR with Vowel, however, was not significant [$F(4,45)=1.81$]. The main effect of Vowel on the combined [±ATR] data was explored with Tukey's tests ($\alpha=0.05$). The low vowel /ɑ/ was found to have higher CQ values than the mean values for the high vowels /i,ɪ/ and /u,ʊ/. The mid vowels /e,ɛ/ and /o,ɔ/ were found to have higher CQ values than the high vowels / i,ɪ/. The results from this analysis indicate that low and mid vowels tend to have greater CQ values than high vowels. Thus, the high vowels are most likely produced with a less constricted glottis and relatively more breathy phonation than the lower vowels.

The [+ATR] vowels were found to have smaller CQ values than the [−ATR] vowels overall. The finding that ATR did not interact with Vowel indicates that the effect of ATR on CQ values was fairly consistent across the five vowel values. Interestingly, this trend was found for the low

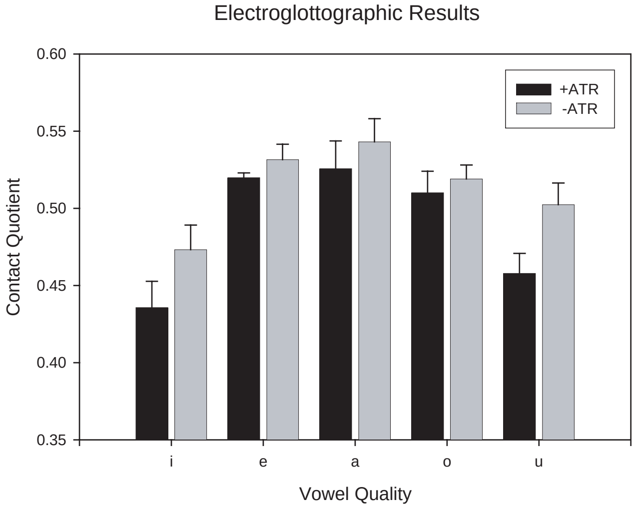

Fig. 5. Mean contact quotients for speaker VK. Contact quotients were obtained by taking the ratio of the closure period to the total period of the vibratory cycle. [+ATR] vowels generally had smaller contact quotient values than [−ATR] vowels, indicating less constriction and thus relatively more lax or breathy phonation for [+ATR] than [−ATR] vowels.

vowels as well (see Fig. 5). Thus, it seems that the [+ATR] vowels are produced with a less constricted glottis and relatively more lax or breathy phonation than the [−ATR] vowels. This effect was consistent across all of the vowel types, including the low vowel.

Given the spectral similarity of the [−ATR] high vowels to the [+ATR] mid vowels, it was considered interesting to determine whether the vowels /ɪ/ and /e/ and the vowel /ʊ/ and /o/ differed in their EGG measurements. The mean CQ values for /ɪ/ vs. /e/ were compared in a one-way ANOVA. The CQ values for the [+ATR] /e/ (.52) were found to be higher than those for the [−ATR] /ɪ/ (.47) [$F(1,18) = 7.68$, $\rho = 0.013$]. The CQ values for /ʊ/ and /o/ were not found to be statistically different [$F(1,18) = 1.06$]. The findings reflect the effect reported above that the mid (and low) vowels tend to have higher CQ values than the high front vowels /i/ and /ɪ/. This difference in phonation type (relatively more breathy for higher vowels) may serve to differentiate [+ATR] /e/ from [−ATR] /ɪ/ for this speaker.

4. Summary and discussion

The effects of [±ATR] on phonologically corresponding vowel pairs (/i,ɪ/, /e,ɛ/, /o,ɔ/, /u,ʊ/and /ɑ/ in [+ATR] and [−ATR] contexts) were consistent across the five speakers (see Table 2 for a summary of the findings). First, vowel duration and F2 frequency did not reliably distinguish the vowel pairs. Second, F1 values were lower for [+ATR] than [−ATR] vowels for all but the low vowel. This difference can likely be attributed to a larger pharyngeal cavity with lower resonant frequency for the [+ATR] vowels. Fourth, there was a tendency for [+ATR] vowels to have a

Table 2
Summary of the significant effects for the ATR pairs for five speakers

Measure	Result
Duration	ns.
F2	ns.
F1	[–ATR] > [+ATR] for i/ɪ, e/ɛ, o/ɔ, u/ʊ
Normalized A1–A2	[+ATR] > [–ATR] for (e/ɛ, u/ʊ)
Closure quotient[a]	[–ATR] > [+ATR] for all vowels

[a] These measures are for speaker VK only.

Table 3
Summary of significant effects for [–ATR] /ɪ/ vs. [+ATR] /e/

Measure	VK	KN	LK	MS	KM
Duration	ns.	ns.	ns.	ns.	ns.
F1	e > ɪ	e > ɪ	ns.	ns.	ns.
F2	ɪ > e	ns.	ns.	ns.	ns.
Normalized A1–A2	ns.	ns.	ns.	e > ɪ	e > ɪ
Closure quotient	e > ɪ				

greater Normalized A1–A2 than [–ATR] vowels. Thus, the [+ATR] vowels tend to have a relatively steeper spectral slope than their [–ATR] counterparts. This could be due to either relative damping of the higher frequencies or relative amplification of the lower frequencies in the [+ATR] vowels.

Several possible causes for the difference in spectral slope present themselves. The first possibility is that there may be a difference in phonation type. Namely, the [+ATR] vowels may have less energy in the higher frequencies due to more breathy phonation, or conversely, the [–ATR] vowels may have more energy in the higher frequencies due to more tense or creaky phonation. The next possibility is that the lower frequencies of the [+ATR] vowels may be relatively less damped due to the greater muscular tension of the wall of the expanded pharynx. Finally, the lower frequencies of the [–ATR] vowels may be relatively more damped due to greater air viscosity in the constricted pharynx.

The EGG data from speaker VK indicates that phonatory differences in [+ATR] and [–ATR] vowels may contribute to the spectral slope described above. The [+ATR] vowels had lower closure quotients and thus were probably produced with a less constricted glottis, creating a relatively more lax or breathy phonation. Interestingly, the differences in phonation between [+ATR] and [–ATR] vowels are not readily perceptible to the authors.

There was variation among the speakers when the differences between, /ɪ,e/ and /ʊ,o/ were investigated, often aligning with the regional origin of the speakers. Consider Tables 3 and 4 and note that participants VK and KN are from the Kilgoris area and the Il-Wuasinkishu section. They both tended to differentiate the [–ATR] high vowels and [+ATR] mid vowels in terms of F1.

Table 4
Summary of significant effects for [−ATR] /ʊ/ vs. [+ATR] /o/

Measure	VK	KN	LK	MS	KM
Duration	o > ʊ	o > ʊ	o > ʊ	o > ʊ	o > ʊ
F1	o > ʊ	o > ʊ	ns.	o >ʊ	ns.
F2	ns.	ns.	ns.	ns.	ns.
Normalized A1–A2	ns.	ns.	ns.	ns.	ns.
Closure quotient	ns.				

Participants MS and KM are from the Kajiado region and Il-Purko section and, unlike the other participants, differentiate /ɪ/ and /e/ in terms of the Normalized A1–A2 measure. Participant LK is from the Il-Keekonyokie section and Narok region and does not differentiate /ɪ/ and /e/ along any of the dimensions investigated. Interestingly, all the participants distinguished /ʊ/ and /o/ by duration, with /o/ being longer. If this difference proves to be reliable, it would seem to be a major cue for this distinction.

5. Conclusion

The phonetic features found to correlate with ATR distinctions in other, mostly Niger-Congo languages, were found to correlate with the ATR distinction in Maa as well. In agreement with many previously studied languages having an ATR distinction, the first formant was found to be lower in [+ATR] than [−ATR] vowels in Maa. This difference is likely due to the lower resonance of the larger pharyngeal cavity in the [+ATR] vowels, though no articulatory investigation has confirmed this for Maa. The spectral slope was found to be generally steeper for [+ATR] than [−ATR] vowels in Maa. This acoustic correlate of the ATR distinction was found previously for Degema [±ATR] vowel pairs (Fulop et al., 1998), using the same A1–A2 normalization procedure. However, the articulatory origin of the spectral slope difference remains speculative. In an electroglottographic investigation of phonation not previously conducted with other ATR languages, data from one speaker indicate that the [+ATR] vowels are produced with a slightly less contact during the phonatory cycle.

What is perhaps different about Maa from previously documented languages is the relative strength of the voice quality correlate. Even though Tucker and Mpaayei (1955) report a voice quality distinction for the Maa speakers they worked with and author DLP has heard voice quality distinctions with Maa speakers on various occasions, we could not detect any readily discernable voice quality distinctions in the recorded data of any of the five speakers investigated here. The finding that, nonetheless, small phonatory differences do exist for at least one of our speakers suggests that a slightly more open glottis may be physically related to an advanced tongue root. Kingston et al. (1997) suggest that voice quality may depend on tongue root “if the aryepiglottal ligament and membrane, which connect the tongue root to the arytenoid cartilages via the epiglottis, cause the arytenoids to slide forward slightly and/or rock slightly apart, slackening or separating the vocal folds enough to lax the voice, when the tongue's root is advanced or raised'' (p.1697) (see also Halle & Stevens, 1969 for a discussion of the possible linkage). If indeed this is the case, the auditory effect seems to be minimal.

However, such an articulatory linking between advanced tongue root and slightly laxed voice could provide an explanation for the origin of stronger and more distinct voice quality cues in other ATR languages and, perhaps, other Maa speakers or speech styles. If the slightly more breathy advanced tongue root vowel is an unintended consequence of pharyngeal expansion, it may present a possible perceptual cue that could be elaborated and phonologized as part of the vowel, eventually creating a robust voice quality difference. Languages may adaptively select for covariation of advanced tongue root and breathy voice because of the auditory mutually enhancing properties of these two features. Kingston et al. (1997) have demonstrated that a low F1 and spectral consequences of breathiness (namely, relatively more low frequency energy) can combine into a single, integrated perceptual cue to advanced tongue root, ''flatness''. A language in which both the cues of F1 and voice quality were exploited fully would perhaps have a more robust ATR contrast than a language that did not fully use both cues.

Finally, returning to the historical questions posed in the introduction, it seems that, whether or not there were two low vowels in the history of Maa, there is only one low vowel presently. This statement is based on the finding that there was no effect of ATR context on the low vowel with respect to formant structure, spectral slope, and duration. However, there were small voice quality differences recorded with the EGG data for the low vowel in the two ATR contexts. We suggest that this finding is evidence of coarticulation with the surrounding vowels. In addition, the /ʊ,o/ comparison revealed a length distinction common to all five speakers. Perhaps the Maa /ʊ/, a reflex of the Proto-Eastern Nilotic short *u, has maintained something of its historically short nature with speakers using length to differentiate it from Maa /o/. The /ɪ,e/ comparison, on the other hand, did not reveal any consistent differences. Most speakers seem to maintain some sort of difference between the vowels, but they varied widely in the way they cued the difference. Perhaps the /ɪ,e/ contrast is not reliably cued by all Maa speakers. If so, the lack of a reliable /ɪ,e/ perceptual contrast may lead to their eventual merger.

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Appendix A. Maa words used in the study

+ATR		−ATR	
[i]		[ɪ]	
kítóóʃò	You hit me.	kɪ́tɔ̀bɔ̀lɑ̂	We held it by its mouth.
èlèpítò	She is milking.	ɛ́jlɛ́pɪ́tɑ̀	He is going up.
èntít$^{!}$ó	girl	ɛ́jdtɛ́tɪ́dɛ́tɪ́tɑ̀	He is dreaming.
èné étídʒíŋjê	They went in through here.	èné ɛ́tɪ́dʒɪ́ŋɑ̂	This is where he entered. This is where they entered.
èɾíkótó	leadership	ɛ́ɾɪ́kɪ́tɑ̀	It is causing nause!a.
tópìɾò	Be fat!	ɑ̀jpɪ̀ɾʊ	to originate
èɾìkí	He will be led.	ɑ̀jrɪ̀kɪ́	to drive in, incite to fight
ɑ̀jtòkí	to do again	ɑ̀pɑ̀lɑ̀kɪ́	to leave to, forgive
ɑ̀jdík	to join	ɑ̀jdɪ́k	to throb with pain
òlbítír	warthog	ɑ̀jpɪ́r	to face
[e]		[ɛ]	
épédʒ	He will burn it.	ɛ́pɔ́k	He will survive.
épét	She will plaster it.	ɛ́pɛ́tɑ́ɑ̀	He will lie on (something).
éból	He will open it.	ɛ́bɔ́l	He will hold its mouth.
ékéd	He will climb.	ɛ́kʊ́r	He will tighten a leather rope.
ésót	She will gather (something).	ɛ́sɛ́k	He will wrangle/get the better of.
èpídʒù	It becomes sharp.	ɛ̀pɪ́	It is sharp, pointed.
èdóɾù	It becomes red.	ɛ̀dɔ́	It is red.
èɾìkí	He will be led.	ɛ̀ɾɔ́k	It is black.
èlépò ɛ̀ŋkítɛ̀ŋ	The cow is in milk/lactating.	ɛ́jlɛ́pɪ́tɑ̀	He is going up.
èmpùtét	tweezers	kɪ̀ɾɔ̀tɛ́t	favorite, popular
[ɑ] in [+ATR] context		[ɑ] in [−ATR] context	
ɑ̀pédʒ	to burn	ɑ̀pɛ́	to be wild
ɑ́tɑ́ɾɑ́póʃè	I have had enough to eat.	ɔ̀sɪ́ɾɑ́tɑ́	mark, line
òlmwɑ́ɑ́tè	deserted site	ɛ̀ɑ́kʊ̀ kɪ̀tók	I shall be great.
ètɑ́lépó	She milked it.	ɛ́mʊ́kɑ́ɾɛ̀	brewing
ɑ́tɑ́ɾɑ́póʃè	I have had enough to eat.	ɔ̀sɑ́rgɛ́	blood
ɑ̀ók	to drink	ɑ̀ɔ́r	to divide
ɑ́í	my	ɑ́ɪ́	other
ɑ̀pɑ̀lɑ̀ɾí	to give up	ɑ̀pɑ̀lɑ̀kɪ́	to leave to, to forgive
kɑ́kè	but	ɛ́ɾɑ́ ɑ̀pɑ́ sɑ́pʊ̀k	He was big.

ɑ̀ŋɑ̀ɾíé	to share food/anything with/ to eat with	ɔ̀lɑ̀pʊ̀tɑ́ní	wife's father
[o]		[ɔ]	
ésótítò	She is gathering (something).	ɛ́tɔ́tɔ́nɑ́	He stayed/sat down.
tóbìkò	Survive!	tɔ́dɔ̀ɾɑ̀	Be red!
òlkútù	skin of dead cow	ɔ̀lkɛ̀dʒʊ́	river
òsésèn	body	ɔ̀sɑ́rgɛ́	blood
èdóɾù	It becomes red.	ɛ̀tɔ̀bɔ́ɾɔ́ ɛ̀ŋkítɛ̀ŋ	The cow has calmed down.
ɑ̀jtòkí	to do again	ɛ̀ŋkɔ̀tí	small calabash
òlkìdòŋôj	mud formed from rain and old dung	tɔ́dɔ̀ɾɑ̀	Be red!
ìlɑ̀rìpók	guards	ɛ́pɔ́k	He will survive.
éból	He will open it.	ɛ́bɔ́l	He will hold its mouth.
éjpòt	He will call.	ɛ́jpɔ̀ʃ	He will churn.
[u]		[ʊ]	
èpùkù	It will come out.	ɛ̀pʊ̀ʃʊ	He was enraged. /He will become enraged
éjpùk	He will flee.	ɛ́jpʊ̀t	He filled it.
òlkútù	skin of dead cow	ɛ̀ŋkʊ́tʊ́k	mouth
èntúkùtùk	motorcycle	kɑ̀tʊ́kʊ̂l	quite, completely
èkúsò èŋkítòk	The woman is dressed up	ɛ́tʊ́sʊ́dʒɑ́	She followed him.
èŋkúkúɾí	calabash	ɛ́sʊ́lʊ́ɲjɛ̀	It will fall from it (e.g. a tree).
èmpùtét	tweezers	ɛ̀ŋkɑ̀pʊ̀tí	engagement (marriage negotiations)
ɑ̀jdʒùlùdʒúl	to decant	ɑ̀jdʒʊ̀lʊ̀dʒʊ̀lɑ́	to be overturned
ɑ̀jdʒùlùdʒúl	to decant	ɑ̀jdʒʊ̀lʊ̀dʒʊ̀lɑ́	to be overturned
édʒút	He will wipe it.	ɛ́sʊ́dʒ	He followed it.

Note: These words are presented here in a broad IPA transcription, but they were presented to the Maa speakers in Swahili-style writing which does not indicate tone or ATR distinctions, along with the English translations. The speakers reported being familiar with all the above words. The underlined vowel was used in the analyses reported here.

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