Contrastive tone and its implementation
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1. Assumptions and major research questions

Tone is defined as a lexically-contrastive pitch pattern (Pike 1948, Yip 2002, Gussenhoven 2004). Not all languages use pitch to create lexical contrasts, but the majority do (Fromkin 1978, Yip 2002). Tone contrasts may consist of different pitch levels (from 2 to as many as 5), or of pitch movements of varying direction, slope and shape: see Figures 1 and 2 for two examples. While pitch changes constantly, and for many reasons, across an utterance, a laboratory phonology approach to tone assumes that there are categorical elements that underlie the constantly changing F0 trace and its articulatory and perceptual correlates. Thus the laboratory phonology approach to tone can be defined as the use of experimental techniques to study the acoustic, articulatory, and perceptual correlates of tone, in order to learn about the underlying categories, and the relation between the underlying representation and its phonetic manifestations, including the co-ordination between tonal and non-tonal elements. Important questions that arise in the study of contrastive tone include:

1. What is a possible tonal contrast?
2. How should tonal contrasts be represented?
3. How are the contrastive features realized in the articulatory, acoustic, and perceptual domains?
4. How are tones aligned with segments and/or larger prosodic constituents?
5. How do tonal systems arise and change?
6. How are tonal systems acquired or learned?

Section 2 of this contribution summarizes some of the answers to these questions that have been proposed in the literature. In each case the issues, major proposals, and phonological evidence will be briefly described. Section 3 then summarizes and exemplifies different laboratory approaches that have been taken to studying these questions. While the study of tonal alternations is important in addressing these questions, tone rules will not be a focus of this section: see [x-ref].

2. Issues and proposals in the phonological literature

The question "What is a possible tonal contrast?" may be rephrased as "What are the necessary and sufficient universal tone features?" (Fromkin 1978:1; see also other contributions in that volume). Research on tone features has focused on establishing which aspects of the pitch pattern are significant – what speakers are paying attention to and systematically manipulating.

Currently, most phonologists agree that the representation that best accounts for cross-linguistic patterns of tonal contrast and alternation consists of H and L autosegments associated to a tone-bearing unit (TBU) such as the mora or syllable (see, e.g., Yip 1989, 1995, 2002, Duanmu 1994, Zhang 2002, Gussenhoven 2004; following Leben 1973, 1978, Goldsmith 1976, Gandour 1974a, Anderson 1978). Languages where the tonal contrasts consist of distinct (relative) pitch levels ("register tone languages" in the terminology of Pike 1948), contrast in the presence of H vs. L (or H vs. L vs. Ø) for every TBU, while "contour tone languages" allow multiple associations for each TBU, so that a rising pitch pattern, for example, is represented by LH. More complex systems may require additional intermediate class nodes: Yip (1995), for example, argues for the addition of a register node [+/- upper] in order to account for systems with more than 3 pitch levels. (See also Yip 2002, Odden 1995, Gussenhoven 2004 for further discussion of tone feature geometry.) The "decomposition" of contours accounts for cases such as "tonal melodies" that spread over the required number of syllables, and tonal alternations which treat the parts of a contour tone separately (Goldsmith 1976). In addition, an autosegmental representation allows for a consistent formalism to be used for register tone, contour tone, pitch accent, and intonation, with varying systems differing only in the sparseness of the tonal representation (McCawley 1978, Pierrehumbert 1980).

A drawback of the autosegmental approach, however, is that the correspondence between autosegments and the parameters of perception and production is not always straightforward. Acoustically, the complex shapes of contour tones do not necessarily consist of an obvious sequence of H followed by L. In the perceptual domain, a number of studies such as those by Gandour (1978 ff.), have shown that listeners judge similarities between tones based on shape rather than endpoints. Thus, some researchers (e.g., Sapir 1921, Pike 1948, Gandour 1978, Abramson 1978, Clark 1990, Xu 1998, 2004, Roengpitya 2007, Barrie 2007) have argued that a representation of tone based on movement rather than high or low points is more phonetically accurate and psychologically plausible. These argue, following Pike, that some languages encode pitch differences in terms of levels ("static targets"), others in terms of movements ("dynamic targets") and that "for a dynamic target, the movement itself is the goal." (Xu 2004:13).

Both the autosegmental and non-compositional approaches to tone features take acoustic or perceptual targets, either movements or endpoints, as basic. Another recent approach (Gao 2006) has suggested using articulatory gestures as the units of tonal contrast. A strength of this approach is that it incorporates tone into the theory and practice of Articulatory Phonology (Browman & Goldstein 1992), which had previously been implemented primarily for segmental phenomena. The articulatory approach to tone has had success in modeling some complex patterns with simple underlying gestures. A weakness is that it is still largely untested, and much further work will be required to test it against a range of cross-linguistic patterns.

Each approach to tone features must also address the question of the co-ordination of the tonal melody with other speech events. One approach to this problem focuses on the identity of the TBU: are there universal constraints governing the association of tones to prosodic units, or will the units and principles of association vary from language to language? (See the discussions in Clark 1990, Odden 1989, 1990 Clements 1984, 1986, Pulleyblank 1994, Duanmu 1994, Yip 1995, 2002.) Another approach focuses on the alignment of tonal specifications to segmental or syllable-level landmarks. Studies of alignment from the dynamic targets perspective include Xu (1998, 1999) and Roengpitya (2007): these studies find evidence for treating tone slopes as indivisible entities. From the autosegmental perspective, studies including Myers (1996), Morén & Zsiga (2006) and Zsiga & Nitisaroj (2007) argue that H and L targets align independently. Other studies of the interaction of tone and prosodic structure have examined the relationship between vowel length and the distribution of tonal contours (Ohala & Ewan 1972, Blicher et al. 1990, Zhang 2002, Yu 2006), the mutual effects of tonal and intonational specifications

(Downing 1989, Inkelas & Leben 1990, Meyers 1996), and the attraction of pitch peaks to prominent TBU's (Bickmore 1995, Yip 2001, de Lacy 2002).

A further question related to tone features is whether "tonal" contrasts sometimes involve dimensions other than pitch, particularly voice quality. In a number of languages, voice quality conveys lexical contrast in a manner similar to tone, or tone and voice quality vary together: for example, a high-toned syllable may always be realized with breathy voice, or a low-toned syllable with creaky voice. Such "mixed systems" are common in Southeast Asia (e.g, Vietnamese, Brunelle 2009)) and in the Americas (e.g., Yucatec Maya, Gussenhoven 2004). To some degree, the treatment of mixed systems is a matter of definition: should the definition of "tone" be revised to include laryngeal contrasts other than pitch? One solution is to adopt a feature system that encompasses all laryngeal contrasts within a single system, such as [+/- stiff] or [+/- slack] vocal folds as proposed by Halle & Stevens (1971). To the extent, however, that both voice quality and tone are controlled systematically and independently, as is the case in many languages, a cross-classifying set of features is needed (see Yip 1992, Andruski & Ratliff 2000, Brunelle 2005, Keating & Esposito 2007). The interaction of tone and voice remains an active area of research. Acoustic and articulatory studies document the co-occurrence of voice and tone parameters, while perceptual studies address the question of whether one or the other aspect has precedence as a perceptual cue.

Finally, questions of how tonal systems arise and change must be addressed, both for the system as a whole and for the individual. Segmental and prosodic effects are particularly important in addressing tonogenesis (the process by which pitch becomes lexically contrastive in a language) and diachronic change (Hyman 1978). Numerous researchers (e.g. Connell 2002, Kingston 2005, Abramson et al. 2007, Svantesson & House 2006) have supported the hypothesis of Hombert et al. (1979) that tonogenesis comes about when pitch differences that are the unintended result of a particular laryngeal configuration are reinterpreted as intended. Concerning individual change, studies of how an individual acquires a tonal contrast in a first language (L1) or learns a tonal contrast in a second language (L2) have lagged behind studies that address segmental acquisition and learning. Crucial questions in both L1 and L2 thus often focus on how the acquisition of tone may be the same as or different from the acquisition of segmental contrasts (e.g., Li & Thompson 1978, Tsukada et al. 2004, Hao & de Jong 2007). The question of how systems of tone and intonation interact in adult learners has also recently become an important area of interest (e.g., Francis et al. 2008, Nguyen & Macken 2008).

There is no one-to-one relationship between the questions listed above and different laboratory approaches. Multiple questions might be addressed, and approaches used, in a single study. The goal of the next section is to briefly review representative laboratory phonology studies of contrastive tone, organized by type of data examined.

3. Laboratory approaches

3.1. F0 measurement

The most common laboratory approach to studies of tone is acoustic measurement of F0 patterns, using pitch tracking algorithms such as autocorrelation [x-ref to methods section]. The most basic example of this type of study is documentation of F0 patterns and contrast in citation form or in an invariant frame. Long lists of descriptive work on languages in every part of the world could be cited, beginning with Bradley (1911); two recent representative examples are shown in Figures 1 and 2. Figure 1 (Picanço 2005) documents three contrastive tones in Munduruku citation forms. Figure 2 (Nitisaroj 2006) documents five contrastive tones in Thai in sentence-initial position. Note that the data in Figure 1 presents actual pitch traces of multiple repetitions by a single speaker, while the data in Figure 2 averages over multiple productions by different speakers, normalized in both pitch range (by transformation to z-score) and duration (% of syllable duration). Both types of presentation are common.

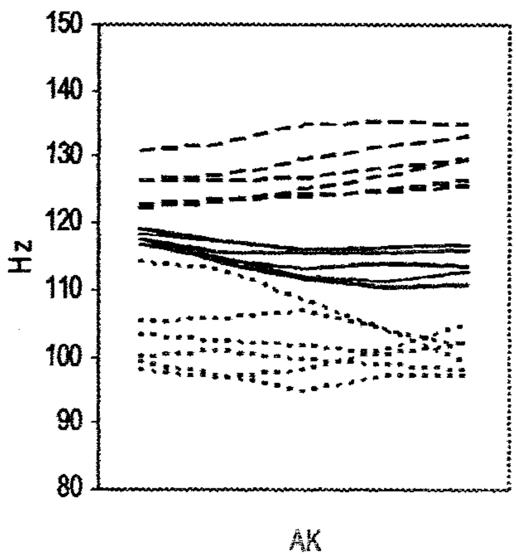

Figure 1. Three contrastive tones in Munduruku (Picanço 2005:46).

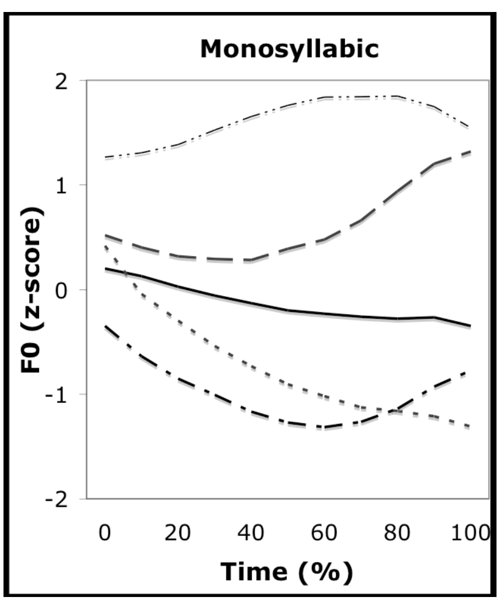

Figure 2. Five contrastive tones in Thai (Nitisaroj 2006).

While studies using citation forms or invariant frames are an important first step, they do not necessarily provide the data needed to uncover the underlying tonal features. A next step is to vary the context: position in the utterance, surrounding tones, or discourse context (such as focus, or statement vs. question). The basic assumption of contextual studies is that aspects of the tonal shape that remain constant reveal underlying features, while changes illuminate the causes of variation.

Contextual studies may address the influence of tones upon one another (Shen 1990, Xu 1997, Gandour et al. 1994, Potisuk et al. 1997, Agwuele 2007, Daly & Hyman 2007); downstep and downdrift in sequences of tones (Hyman 1979, Snider 1998, Connell & Ladd 1990); phrasal and prosodic influences including the interaction of tone and prominence (Yip 2001, Gussenhoven 2004, Morén & Zsiga 2006, Roengpitya 2007), and the interaction of tone and intonation (Downing 1989, Inkeleas & Leben 1990, Myers 1996, Herman 1996, Kallayanamit 2004, Yuan 2004, Hyman 2008). Data from such studies may determine whether contextual changes are more categorical, characteristic of what many would call phonological, or whether they are better characterized as gradient, within-category variation. Data from studies of contextual variation are often used to argue for different models of featural representation. Daly & Hyman (2007), for example, argue that the mid tone in Peñoles Mixtec must be phonologically unspecified, based on varying contextual realizations. Gussenhoven (2004) documents a tonal contrast in Yucatec Maya that is realized with glottalization in phrase-final position, but as a falling contour in phrase-medial position, and argues for a phonological association between glottalization and high tone. Inkelas & Leben (1990) demonstrate a number of phrasal and intonational effects on tone realization in Yoruba, and use the data to argue for the necessity of a register node in phonological representation. Figure 3 illustrates the difference between high and low register in Yoruba tone in a statement and yes-no question.

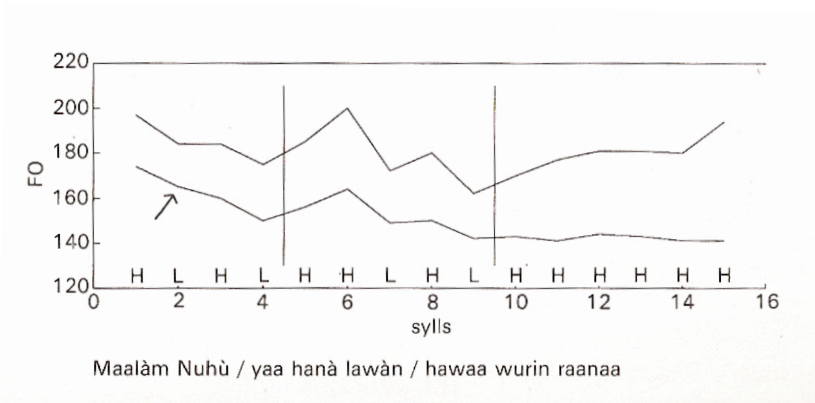

Figure 3: A statement and yes-no question in Yoruba (Inkelas & Leben 1990:18).

Another type of variation is speech rate. Xu (1998), for example, compares the realization of Mandarin tonal contours on syllables of different lengths pronounced at different speech rates, and evaluates changes in the shape and alignment of the contours. He concludes that rising and falling contours move as a unit, rather than peaks and valleys aligning independently, and from this draws support for the hypothesis that contours are "integral dynamic" units rather than being composed of sequential H and L. Roengpitya (2007) reaches a similar conclusion for Thai based on contour realizations over syllables of different lengths. On the other hand, Nitisaroj (2006) finds that H and L points in the contours of Thai align independently under changes in speech rate. Myers (1996) finds a difference only in peak alignment in Chichewa.

Acoustic analysis is also used to study the interaction of tones with vowels and consonants. Early acoustic studies (Peterson & Barney 1952, Lehiste & Peterson 1961, Lehiste 1970) established that high vowels, probably due to the interconnectedness of tongue muscles and the structures of the larynx, have slightly higher "intrinsic" pitch than non-high vowels (see also Ohala & Eukel 1987 for discussion). Whalen and Levitt (1995) and Connell (2002) confirm an intrinsic pitch effect in tone languages, and find that the effect of vowel quality on F0 is greater for high tones than for low tones. Other early studies, such as Hombert et al. (1979), conclude that voiced consonants lower F0 and voiceless consonants raise F0. These studies provided acoustic evidence for voicing distinctions in consonants as a source of tonogenesis, a hypothesis previously based on written sources (e.g., Haudricourt 1954). Teeranan (2007) and Hyslop (2009) provide recent examples of such tonogenesis in progress. Kingston (2005) focuses on glottalization, finding that in some cases glottalization is associated with raised pitch due to increased vocal fold tension, while in other cases it is associated with lowered pitch due to irregular vocal fold vibration. Picanço (2005) uses acoustic analysis of vowels to determine that F0 is a more reliable correlate of lexical contrast in Munduruku than is voice quality. Other acoustic studies of mixed systems (Abramson et al. 2007, Svantesson & House 2006, Brunelle 2009) make diachronic applications: the data show these systems evolving from a voice quality contrast to a mixed system to a pure tone system. Dialectal differences are often evident, with different dialects at different stages. Studies of mixed systems often include both acoustic and perceptual components: acoustic studies to document what voice qualities and tones occur together, and then perceptual studies to determine how varying the combinations changes listeners' judgments.

3.2. Perception studies

The simplest form of tone perception study is lexical identification: native speakers of a language listen to tokens of natural speech and name the word they hear. A lexical identification task can be used to check that the linguist's understanding of the system of is correct – listeners can indeed distinguish the tones that the linguist believes are contrastive – and can serve as a baseline for further studies. Studies based primarily on natural-speech lexical identification include Roux (1995), Peng (1997), Connell (2000), Andruski (2006) and Khouw & Ciocca (2007). Svantesson & House (2006) and Brunelle (2009) introduce dialectal variation, and mechanisms of diachronic change. Svantesson & House find that some dialects of Kammu use F0 for lexical contrast and some do not, hypothesizing that tonogenesis is underway in this language. Brunelle concludes that Northern speakers of Vietnamese use voice quality distinctions that Southern speakers have lost.

To further probe the cues that are necessary and sufficient for a particular contrast, researchers often digitally alter speech tokens for perception studies: resynthesizing pitch contours (Vance 1977, Abramson 1978, Garding et al. 1986, Lin & Repp 1989, Repp & Lin 1990, Zsiga & Nitisaroj 2007, Abramson et al. 2007); filtering to remove F0 information (Liu & Samuel 2004);

truncating syllables (Lee 2001); or combining pitch and other dimensions such as voice quality or duration in different ways (Blicher et al. 1990, Yu 2004, Brunelle 2009). By independently varying the parameters that occur together in natural speech, or requiring listeners to respond to unnatural contours that contain hypothesized cues, perceptual studies with digitally-altered speech can tease apart the effects of different cues that are inseparable in natural speech. For example, Brunelle (2009) shows that perceptual judgments do not correspond to generally-accepted tone features for Vietnamese, and argues in favor of a new system. Abramson (1978) tested the degree of slope that was necessary for Thai speakers to identify a tone as "rising." On the other hand, Zsiga & Nitisaroj (2007) tested various synthetic contours, and conclude that peak alignment, not slope, is the main perceptual cue to tonal distinctions in Thai. Figure 4 (Zsiga & Nitisaroj 2007:377) shows that lexical identifications switched from "falling" (filled diamonds) to "high" (asterisks) as the pitch peak was moved later, with the crossover point occurring about ¾ of the way through the syllable (220 ms). Peaks in the first half of the syllable caused ambiguity and confusion, consistent both with the hypotheses that peaks are aligned to the *right* edges of moras, and with the findings of House (1990) that, cross-linguistically, tones are better perceived later in the syllable, after the spectral changes associated with syllable onsets have subsided.

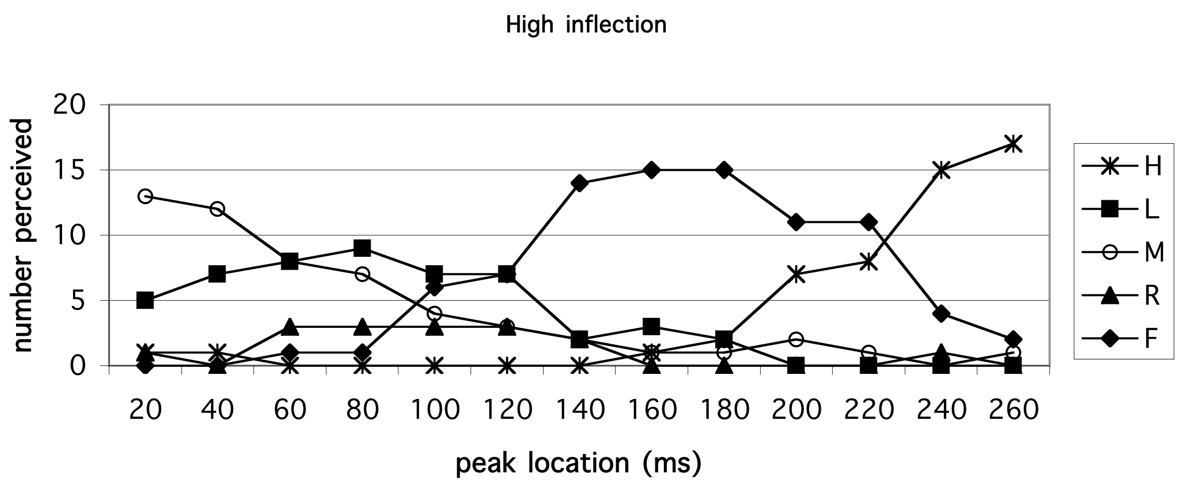

Figure 4: Tone identifications as a function of peak alignment on digitally-altered F0 contours in Thai (Zsiga & Nitisaroj 2007).

Another type of perception study involves asking listeners for similarity judgments rather than lexical identifications, using a same-different (AX) task, or similarity (AXB) task. An advantage of such studies is that listeners do not have to be native speakers of the language(s) under study, or trained in making categorizations. A drawback is that it is not clear whether listeners are using the same strategies for similarity judgments as for lexical judgments (see discussion in Zsiga & Nitisaroj 2007). Gandour and colleagues (Gandour 1978, 1981, 1983; Gandour & Harshman 1978) have used this technique, along with the statistical analysis of "multidimensional scaling," to test whether speakers of different languages use the same dimensions to group pitch contours in the perceptual space. Gandour argues that listeners with different language backgrounds use the same five dimensions, but weight their importance differently: speakers of tone languages give more weight to pitch slope than speakers of intonational languages do, for example. He thus concludes that perceptual features including direction and slope of pitch change must be included as part of the universal feature set. In a recent version of similarity judgment tasks, researchers use PET or ERP studies, relying on known brain responses to within-category and across-category stimuli, to measure directly whether two sounds are perceived as the same or different (Gandour et al. 2000, Li et al. 2008).

A final perceptual issue is how tone normalization works. It is clear that tonal contrasts are relative: a "high" tone does not refer to an actual pitch level, but to a tone realized in a certain part of the speaker's range. Studies investigating how listeners normalize for pitch differences between speakers (Leather 1983, Moore & Jongman 1997) present syllables with identical F0 patterns in different contexts, or vary pitch with other segment-internal information, to determine which changes influence listener decisions.

3.3. Articulatory studies

The earliest form of articulatory study was autopsy. Ohala (1978:10) credits Vesalius (1543) for providing detailed descriptions of laryngeal anatomy based on autopsy. Ohala also cites experiments conducted by Müller (1851) "done using freshly excised human larynges, sometimes with most of the rest of the vocal tract attached," which demonstrated that pitch could be changed both by altering vocal fold tension and by regulating sub-glottal air pressure. Figure 5 illustrates the laboratory setup.

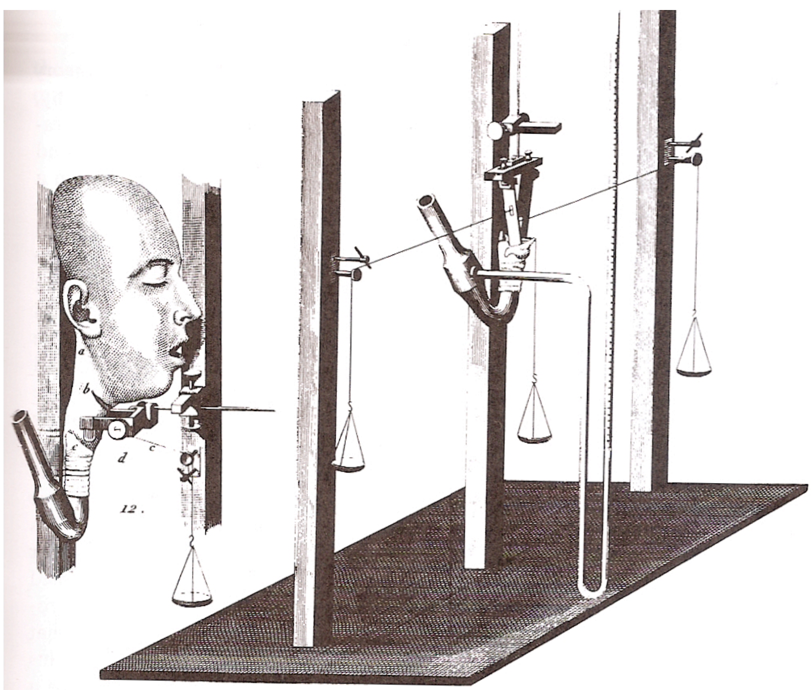

Figure 5. An early laboratory phonology experiment: Müller 1851, reprinted in Ohala (1978).

Modern articulatory investigations of tonal contrast use airflow measures, laryngoscopy, electroglottography (EGG) and electromyography (EMG) [x-ref to methods section]. Studies of airflow focus on the effect that oral constrictions have on trans-glottal airflow and thus (potentially) on pitch. Guion & Wayland (2004), for example, use airflow data to argue that the aerodynamic requirements of an apical trill condition a falling F0 contour, with implications for tonogenesis. Edmonson & Esling (2006) use laryngoscopy to investigate laryngeal mechanisms in the interaction of tone, register, and stress. Brunelle (2005, 2008) uses EGG, among other techniques, to investigate the interaction of voice quality and tone in Cham, and argues for the separation of laryngeal and tonal features.

EMG is a difficult methodology to use for laryngeal studies, because the muscles of the larynx are small, intertwined, and not easily accessible, and because the insertion of the hooked-wire electrodes is not pain free. The technique is therefore most often used in the study of voice disorders (e.g., Heman-Ackah & Barr 2006). Nonetheless, evidence from EMG studies can be useful in establishing whether there is an active articulatory gesture (and thus phonological target) associated with a particular pitch pattern. EMG studies in the 1960's and 1970's established that the cricothyroid muscle is the primary muscle responsible for pitch raising, whereas the sternohyoid and sternothyroid are most active in pitch lowering (Ohala 1978). The technique can be used to investigate whether similar pitch patterns in different languages are brought about by similar articulatory actions, and can thus be useful in defining cross-linguistic features and natural classes (Erickson 1976, 1994, Halle 1994).

3.4. Modeling

Recently, computer modeling has begun to be used in the study of tonal contrast. Computer models and "analysis by synthesis" test whether the right shapes can be derived from the proposed primitives and a given understanding of contextual influences. Languages for which computational models of tonal implementation have been proposed include Mandarin (Shih & Kochanski 2000, Yuan et al. 2002, Yuan 2004, Xu 2004), Thai (Mixdorff et al. 2002, Roengpitya 2007), Vietnamese (Mixdorff et al. 2003), and Yoruba (Agwuele 2007). Fujisaki et al. (2007) apply their model to Thai, Vietnamese, Mandarin, Cantonese, and other Chinese languages. Gao (2006) synthesizes trajectories for Mandarin based on gestural scores. Other models (e.g., Cao et al 2004, Zhang & Hirose 2004) are implemented in speech recognition systems for tone languages.

3.5. Studies with special populations

A final set of experimental approaches to consider is studies with special populations. These studies allow researchers to examine tone systems in development, decline, and conflict in order to provide new evidence for cognitive representations. Studies of L1 acquisition in children (Tse 1978, Lydia & Dodd 1995, So et al. 1995, Tsukada et al. 2004) use perception and production techniques to address the chronology of tone acquisition, differences between the acquisition of tone and segments, and cross-language differences and similarities. Parallel questions can be asked concerning adult L2 learners. In addition, studies of L2 learners can explore ways in which the L1 and L2 systems interfere with one another, and what sorts of interventions may be most useful. L2 studies of tone may focus either on speakers learning a new tone language (Wang et al. 1999, Wayland & Guion 2004, Hao & deJong 2007, Francis et al. 2008, Wayland & Li 2008) or on speakers of tone languages learning a non-tone language (Wayland et al. 2006, Nguyen & Macken 2008). Finally, studies of atypical populations such as patients who have suffered aphasia or stroke (Gandour et al. 1996, 1997, Gandour 1998, Becker & Reinvang 2007) can assess the ways production and processing of tone may change in the damaged system.

4. Conclusion: consensus and directions for further research

None of the questions raised in Section 1 have been fully answered. Research continues on the question of defining tonal systems. Undocumented languages remain to be described. The interaction of voice quality and tone, involving the synchronic and diachronic study of mixed systems, is an especially active research area. Regarding tonal features, the current consensus among phonologists is that tonal representations are autosegmental, but much work remains to be done in determining how these autosegments are produced and perceived, and a number of researchers who pay close attention to perception and to phonetic implemention, especially of contour tones, remain unconvinced. The question of how tones are aligned to other speech events remains an active area of research from all theoretical perspectives. Research on change, acquisition, and learning of tonal systems has in the past lagged behind segmental studies, but is currently increasing. All of the laboratory techniques described in this contribution – acoustic, perceptual, articulatory, and computational – will continue to be used in the Laboratory Phonology study of contrastive tone.

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