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I, Ahmed Rivera Campos, hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Communication Sciences and Disorders.

It is entitled: Using Ultrasound Imaging for Better Understanding of the Apicoalveolar Rhotic /r/

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Using Ultrasound Imaging for Better Understanding of the Apicoalveolar Rhotic /ɾ/

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Abstract

The apicoalveolar trill /r/ is used across various languages of the world including Spanish, Italian, and Persian among many others. While it is widely used by different languages, we still lack a thorough understanding of how it is produced. The apicoalveolar trill /r/ is commonly considered one of the speech sounds most subjected to production errors by children learning their primary language as well as second language learners. Although efforts to understand its production have been made, these efforts mainly focus on the salient aspect of the sound, the apicoalveolar trilling. This has provided thorough understanding of /r/’s articulatory requirements at the anterior parts of the tongue but understanding of the articulatory requirements of the posterior portions of the tongue are unclear. The lack of this knowledge negatively impacts how practitioners can ameliorate /r/ production difficulties on children and adults as there is limited information on best practices for teaching /r/. To address these gaps in the literature—understanding articulatory requirements and development of potential best practices—ultrasound imaging was used as a tool for imaging tongue configuration at the back portions of the tongue as well as a means to teach /r/ production. Our imaging results show that native speakers of various Spanish dialects have a retracted tongue root positioning when producing /r/. In the area of potential best practices for teaching /r/, our results suggest that usage of certain contexts as well as ultrasound biofeedback are useful strategies for teaching acquisition of /r/.

There are inconsistencies in the literature regarding the acoustic profile of /r/. Some author have reported data that suggests a low F3 for /r/—just like the English rhotic approximant—while other authors do not report this observation. There is some evidence that
lowering of the F3 is achieved in part by /u/’s retracted tongue root positioning. With the English approximant and the apicoalveolar trill sharing similar tongue root configuration when produced, it is unclear if a low F3 is also part of /r/’s acoustic profile. Our results suggest that a low F3 is not part of the acoustic profile of /r/ as it is for /u/. Teaching and clinical implications are further discussed.
Dedication

A Ahmed Rivera Guevara e Yvette Campos Camacho, mis padres y mi fundación.

A Yainier Omar Rivera Rodríguez y Kamila Isabel Rivera Rodríguez, mis adorables sobrinos.

No hay palabras suficientes en este mundo para expresar lo mucho que los amo.
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# Table of Contents

Abstract .................................................................................................................................................. 3

Chapter I Overview and Rational of the Study .................................................................................... 10

Chapter II. ............................................................................................................................................ 14

Articulatory Requirements of the Spanish Trill: An Ultrasound Imaging Study of Tongue

Configuration for /r/ by Native Speakers of Spanish .......................................................................... 14

   Articulation of Apicoalveolar Trills .................................................................................................... 16

   Pharyngealization of Consonantal Sounds ......................................................................................... 17

   Tongue Root Configuration for Apicoalveolar Trills ...................................................................... 18

   Tongue Root Configuration of Rhotics from Different Languages ........................................................................ 21

Methods ............................................................................................................................................... 22

   Participants ........................................................................................................................................ 22

   Trill stimuli ......................................................................................................................................... 23

   Equipment and data gathering process ............................................................................................... 23

Results ................................................................................................................................................ 26

   Tongue configuration .......................................................................................................................... 26

Discussion ......................................................................................................................................... 32

   Pharyngeal Constriction ...................................................................................................................... 32

   Role of pharyngeal constriction of /r/ ............................................................................................... 33

   Clinical implications ............................................................................................................................ 34

Chapter III. ........................................................................................................................................ 36

Learning Production of Apicoalveolar Trill /r/ by Ultrasound Biofeedback ...................................... 36
Overview and Rationale for the Study

Acquisition and production mastery of speech sounds is expected to occur in young children as they develop. This acquisition and production mastery of speech sounds does not require formal instruction from practitioners or parents, as children independently decipher how to configure their tongue for producing speech sounds. During this developing period, children seem to acquire and master some speech sounds prior to others; with the later acquired sounds commonly labeled as late developing (Bleile, 2006).

Rhotic Speech Sounds in Early Development

The class of rhotic sounds includes a number of speech sounds with different place and manner of articulation: the class includes uvular fricatives and trills, alveolar trills and palatal approximants, among others. Across many languages, rhotics are commonly the target of production errors until late in development and thus appear in the list of late developing sounds (McLoud, 2007). Unfortunately, some children fail to achieve accurate production of rhotics in the normal course of development, giving rise to intelligibility and social acceptance issues. These children typically improve their production only after formal instruction from professionals.

Rhotic Speech Sounds in Adult Language Learning

Just as rhotic production inaccuracies have been observed in some children, adult second language learners face similar challenges (Face, 2006; Johnson, 2008) and unlike young monolingual typically developing children, adult second language learners are often provided with formal instruction on how to produce rhotic segments that are not shared between their
primary and second language (e.g. Lord, 2005; Hurtado & Estrada, 2010; Añorga & Benander, 2015; Kissling 2013). However some individuals fail to acquire accurate production of rhotics in their second language even after formal instruction has been provided. Since the articulatory requirements of rhotic segments can vary widely across languages, second language learners who have failed to achieve acquisition of the second language’s rhotic segment commonly produce the rhotic segment they have already mastered from their primary language. That is, they substitute rhotic segment production of the second language with the rhotic production from their primary language (Kissling, 2013). These substitutions can lead to intelligibility issues.

The Role of Articulation Knowledge in Formal Instruction

Both children and adults who have failed to acquire accurate sound production of rhotics require the use of formal instructions and strategies to help achieve accurate production these of rhotic segments. These strategies are typically based on articulatory instructions, often using visual models or diagrams. This visual information is then used by the individual to try to duplicate the tongue configuration as best as (s)he can (e.g. Kissling, 2013). However, the articulatory requirements of many rhotic sounds are not well understood. In general, articulatory descriptions of this sound have tended to focus on articulatory positioning and movement of the anterior portions of the tongue (e.g. Remache-Guastay, 2015; Chocho-Guaman & Merchán-Lapo, 2012). Such is the case of the American English approximant /ɹ/ (also written [ə] in certain word positions) and the most common and iconic rhotic, the apicoalveolar trill /r/, which occurs in a number of languages, including Spanish, Persian and Scottish dialects of English. However, the availability of imaging technologies has brought new information to light on the articulation of speech sounds, and on rhotic articulation in particular.
The use of formal instruction and articulatory strategies based on incomplete phonetic information is a problem for clinicians and teachers because it may considerably limit the repertoire of best practices available to a practitioner. Works that focus on increasing our understanding of the articulation and acoustics of rhotics is important because it will enable the development of new clinical and teaching strategies. Studying the effectiveness of these and any other potential best practices would be highly valuable for servicing the needs of children and adults with errors in these sounds.

**Problems Specific to the Trill /r/:** Our limited understanding of the trill /r/ in particular requires more information than is typically found in textbooks. Understanding the acoustics of these sounds may help us understand the impact of misarticulations on the listener. In particular, a better understanding of the phonetics of these sounds, and of /r/ in particular, will be a significant contribution to better clinical intervention for late-developing rhotic sounds, and for adult second language learners.

**Rationale for the Study:** To address some of these gaps from our /r/ literature, the following articles present various research projects which target (1) our understanding of the configuration of the more posterior parts of the tongue during /r/ production, (2) the use of potential best practices for teaching acquisition of /r/, and (3) the acoustic profile of the third formant of /r/. For the first and third research projects, adult native speakers of various Spanish dialects were recruited to produce a series of Spanish words that contained /r/ in different word positions and vowel contexts while using an ultrasound machine to image tongue configuration at the posterior portions of the tongue. To address the second research project, adult native speakers of English
who were learning Spanish as a second language but were unable to produce /r/ were recruited.

Results for each work are further discussed.
Chapter II.

Articulatory Requirements of the Spanish Trill: An Ultrasound Imaging Study of Tongue Configuration for /r/ by Native Speakers of Spanish.

The purpose of this research is to better understand the articulatory requirements of the apicoalveolar trill /r/. Previous research on other rhotics of the world like English /ɹ/ have found that a retracted tongue root positioning is required for /ɹ/ production. Although some phonetic research on /r/ have lightly alluded to the involvement of the posterior portions of the tongue for its production, there is limited information on this issue. Understanding the articulatory requirements of /r/ at the more posterior portions of the tongue is necessary for development of more accurate teaching strategies that can be used for monolingual and bilingual individuals who are struggling with accurately production of /r/ by modifying their vocal tract. As speech sound production is correlated with articulatory gestures that create a series of constrictions that modify the vocal tract, it is important to have good control and mastery of the active articulators--like the tongue, soft palate, mandible, and lips. The tongue, the most active articulator inside the oral cavity, is unique compared to other active articulators, as it is composed of functional segments that can be independently controlled. These segments can be moved in similar or opposite directions that allow for different gestures for speech sounds (Stone, Epstein & Iskarous, 2004). Roughly, in a midsagittal view, the tongue can be described as being composed of tongue tip, tongue blade, tongue dorsum, tongue root (Stone, Epstein & Iskarous, 2004).

When the active articulators for a target phoneme are not adequately positioned, it results in a distorted and misarticulated speech sound that can affect speech intelligibility. Distortions of phonemes are commonly found in young children as they develop and acquire mastery
production of the sounds of their language. During their speech sound development, there are some sounds that are commonly labeled later developing as these are the last sounds to be consistently produced without being misarticulated (Bleile, 2006). Typically developing children are able to acquire and master later developing sounds of their language without formal instruction. However, some children persist with articulation errors, often identified as having a disorder and consequently referred for treatment. Although they are not considered to show a disorder, adults who are learning a second language can also show sound distortions on speech sounds. This is most notable when the speech sound is not shared between the primary and second languages.

One speech sound type that is late-developing and subject to many articulatory errors is the class of rhotic sounds. Descriptions of speech sound acquisition patterns in many languages of the world include the observation that rhotic phonemes are particularly challenging for language learners in many different languages of the world. These include English (Shuster, Ruscello, & Toth, 1995), Arabic (Amayre & Dyson, 1998), Catalan (Bosch 2005) and Spanish (Jimenez, 1987; Goldstein, 1999; Bosch, 2005; Boyce, Hamilton, & Rivera-Campos, 2016), among others.

Some languages use more than one rhotic as part of their phonemic inventory. In the case of Spanish, two apicoalveolar rhotics are used, the tap and the trill, which are also phonemically contrasted in intervocalic position as well as being articulated differently; the tap /ɾ/ and the trill /r/ (Ladefoged and Maddieson, 1996). This phonemic contrast occurs in minimal pair words like /karo/ (expensive) and /karo/ (car). Although both rhotics in Spanish are considered later developing, children master production of tap before the trill (Bosch, 2005).
With the tap having a mastery age by six and the trill by seven years of age (Bosch 2005; Goldstein, 1999; Acevedo, 1993; Jimenez, 1987). However, some children are unable to acquire and master /ɾ/ production even after the expected age and are referred to professionals for treatment. Additionally, there is a fraction of children who still show /ɾ/ misarticulations even after undergoing treatment. In adults who are native speakers of English and are learning Spanish as a second language, the Spanish trill also poses a challenge, with a significant fraction of adult learners unable to produce /ɾ/ even after becoming fluent in the language.

**Articulation of Apicoalveolar Trills**

Many investigators describe /ɾ/ as being articulated by stopping the airflow with a brief direct movement of the tongue’s tip against the alveolar region (Ladefoged & Maddieson, 1996; Fernandez 2000; Quilis & Fernandez, 1992). This single brief direct movement of the tap perceptually distinguishes it from the vibratory state characterized during the production of the apicoalveolar trill /ɾ/. Although it is common to describe apicoalveolar trills as having multiple brief contacts against the alveolar area, the tip of the tongue does not always touch the alveolar region during trilling (Whalen, Iskarous, Grathwohl & Proctor, 2010; Blecua, 2001). Trilling occurs when a soft and moveable articulator or section of one—most commonly the tongue’s tip or uvula—is set to a vibration pattern against another articulator by aerodynamic forces (Ladefoged & Maddieson, 1996). In the case of the /ɾ/, aerodynamic forces create the Bernoulli effect and make the tongue tip enter into a vibratory state in the alveolar region (Martinez-Cekran, 1997). This aspect of /ɾ/—trilling of the tongue tip—can make this sound challenging to master for children and for individuals learning a second language.
The late acquisition of /r/ and the challenge it might posit to some individuals has created the necessity of research aimed at describing its articulation requirements. Most of these works have focused on describing the fast and multiple apicoalveolar constrictions. Some native speakers of Spanish produce /r/ with a variable number of phases (opening and closing phases of the trilling) that can range between three components (closing phase, an opening phase, and another closing phase), four components (closing, opening, closing and opening phases), and five components (closing, opening, closing, opening, and closing phases) (Blecua, 2001).

The topic of aerodynamics and trilling during /r/ production was further expanded and detailed by Solé (2002) as the author described how small changes in pressure can create a devoiced allophone (voiceless trill) or cessation of trilling as well as the amount of intraoral pressures required for trill initiation and maintenance of voiced and devoiced /r/. Recasens and Pallarès (1999) studied /r/ in VCV sequences. The authors found that /r/ has a more constrained tongue configuration when compared to the tap /ɾ/ and that /r/ exerts more coarticulatory displacement to contiguous vowels than vowels to /r/. According to the authors, this exertion was observed on all vowels, but /i/ showed the greatest displacement. Overall, the evidence suggests that /r/ has a very precise and complex tongue configuration requiring that speakers develop significant mastery of tongue configuration required for /r/ in connected speech.

Pharyngealization of Consonantal Sounds

Consonantal sounds are commonly described and categorized by their main constriction along the vocal tract. However, this method of categorization can be considered too broad for representing accurate tongue configuration for speech sounds.
Some researchers have suggested a more descriptive way of describing how a speech sound is articulated by describing any co-occurring secondary constriction in addition to the main constriction. Ladefoged and Maddieson (1996) used the term “pharyngealization” as a term to describe a co-occurring secondary constriction at the level of the pharynx. This pharyngealization is usually found in vowels and certain consonantal sounds from some Arabic dialects whose speakers use pharyngealization to differentiate between plain and emphatic coronals (i.e. /s/, /s̝/). Ladefoged and Maddieson (1996) as well as the dark /l/ in speakers of English Narayanan, Alwan & Haker (1997) and Catalan dialects of Valencia and Mallorca (Recasens & Espinosa 2005). Narayanan, Alwan and Haker (1997) described a tongue root retraction that can be accompanied by a posterior raising of the tongue body for the articulation of dark /l/ while Recasens and Espinosa (2005) uses the term velarization and/or pharyngealization to describe the back movement of the tongue by analyzing the acoustic signal of dark /l/ of both Catalan dialects. For only a certain amount of rhotics Magnuson (2007) suggested pharyngealization as an articulatory requirement. But due to lack of empirical evidence and imaging data, the author excluded /r/ as a pharyngealized rhotic. That is, if the /r/ has a retracted tongue root positioning that creates a constriction at the level of the pharynx.

### Tongue Root Configuration for Apicoalveolar Trills

Some studies have described the /r/ as a geminated of the tap (Núñez-Cedeño 1994; Harris 2002) while other studies (Shelton, 2013; Colina 2010, Bradley 2006, Delattre, 1971) have gathered data that suggests that /r/ does not derive from an underlying geminate, that is, /r/ is not made by doing multiple times the articulatory gestures made for the Spanish tap. If one sound is not a geminate form of another it is likely that it has a different tongue configuration.
Using Ultrasound Imaging for Better Understanding

and different tongue positioning along the vocal tract. Lingual-palatal contacts of tongue tip and blade for /ɾ/ and /r/ show differences on where the contacts are made within the alveolar region (Recasens & Pallarès, 1999). These lingual-palatal contacts in the alveolar region show that /r/ has a place of articulation at a more retracted place when compared to /ɾ/. These differences in lingual-palatal contacts can make acquisition and mastery of /r/ a challenging task as individuals must make precise location adjustments of tongue tip/blade positioning along the alveolar region for each rhotic. For /ɾ/, lateral sides of the tongue become raised making a groove along the middle portion of the tongue (Navarro-Tomas, 1996; McGowan, 1992). Additionally, the height of the dorsum is lowered as tongue tip and blade are raised towards the alveolar region (Proctor, 2011). Tongue root position for /ɾ/ production is commonly absent or vaguely suggested. Commonly, it is left to interpretation by describing a general movement of the tongue body towards the back of the mouth. This issue might stem from the location of the tongue root as it is located far back in the oral cavity and it can be easy to overlook. Additionally, when producing speech sounds, individuals are less proprioceptively aware of the positioning of the tongue root as tongue root contact with other articulators is seldom involved for speech sounds.

Previous work describing tongue configuration for /ɾ/ had provided vague suggestions of tongue root involvement that is sometimes attributed to coarticulation, sometimes observed and described but not attributed to /ɾ/’s articulatory requirements, sometimes implicit by describing other aspects of /ɾ/, and sometimes just not considered at all. Additionally, as part of their descriptions, authors use terms that can be interpreted variously (i.e. tongue body, tongue back, tongue dorsal, postdorsum etc.). In his manual for the pronunciation of Spanish sounds, Navarro Tomas (1996) described /ɾ/ production as having a tongue body that moves towards the back of the mouth. This description leaves open to interpretation if tongue root involvement is an
intrinsic aspect for /r/ articulation as some speech sounds also have a back movement of the tongue body but not necessarily a back movement of the tongue root (Boyce, Hamilton and Rivera-Campos, 2016). Visual inspection of Delattre's (1971) X-ray tracings for the Spanish words /remo/ (oar) and /pero/ (dog) show a constriction at the level of the pharynx made by the tongue root during /r/ but the author did not address this constriction as a possible articulatory requirement for Spanish /r/. In fact, a brief mentioning of a movement at the back of the tongue for /r/ during /pero/ is attributed to coarticulation from the upcoming vowel /o/. Tongue configuration for /r/ is described by Proctor (2011) as resembling a mid-back vowel /o/ and by having tongue dorsal raising and retraction when produced in a_a context.

A study on the coarticulatory effects between vowels and /r/ by Recasens and Pallarès (1999) found that /r/ has stronger coarticulatory effects on vowel production than vowels onto /r/. The authors explained that some vowels exhibited changes on where along the vocal tract they were made while vowels had little to no effect on where /r/ was made along the vocal tract. These observations by Recasens and Pallarès leave open to interpretation a possible role of tongue root involvement for /r/ production or if it is a behavior of coarticulation during certain contexts. While studying the required intraoral pressures needed for initiating and maintaining trilling in /r/, Solé (2002) stated that adequate /r/ production required certain ranges of intraoral pressures—which varied for voiced and voiceless /r/- as well as exhibiting a restricted place of articulation. Although speculative, a restrictive tongue placement for /r/ might be due to tongue root involvement.

Imaging data on native speakers of Spanish have briefly mentioned the presence of a retracted tongue root positioning. Describing an alternate tongue configuration were some native
speakers of Spanish used the lateral sides of the tongue for trilling instead of the commonly describe tongue tip, Rivera-Campos and Boyce (2013) briefly mentioned that a back movement of the tongue root was observed on all /r/ instances—including the ones where the alternate tongue configuration was used. A later pilot study by Rivera-Campos and Boyce (2013) focused on assessing this back tongue root movement during /r/. Their data also suggested the presence of this retracted tongue root positioning. However, the number of participants in that study was limited, and more empirical data was needed to see if this retracted tongue root positioning is an articulatory requirement of /r/. There is some evidence suggesting that trill rhotics across languages share a co-occurring secondary constriction at the level of the pharynx characterized by a retracted tongue root positioning (Boyce, Hamilton, Rivera-Campos, 2016). Complexity of this type may help us understand why a sound can be challenging to acquire and master.

**Tongue Root Configuration of Rhotics from Different Languages**

Better understanding of the articulatory requirements of certain rhotic consonants of different languages of the world has been made possible by the use of imaging technologies. Tongue configuration of rhotic consonants from languages like English, Malayalam, Russian, Turkish, Persian, and French has been described on studies using imaging techniques like magnetic resonance imaging (MRI), ultrasound, and X-rays. With advances in technology, ultrasound is becoming a more common tool for imaging tongue configuration during speech sounds and an increasing number of studies have started to provide attention to the positioning of the posterior parts of the tongue including tongue root for rhotic consonants. For the English approximant, Tiede, Boyce, Holland and Choe (2004)—using MR imaging and ultrasound—a co-occurring secondary constriction at the level of the pharynx characterized by a retracted
positioning of the tongue root is required, which was also suggested by Delattre and Freeman using X-ray tracings (1968). Hamilton and Boyce (2013) studied tongue configuration in Turkish rhotics /ɾ/ and /ɾ/.

The authors also described a retracted tongue root positioning for the rhotic segment when native speakers of Turkish produced words containing /ɾ/. Interestingly for /ɾ/, the native speakers of Turkish showed that this retracted tongue root positioning was variably present. Malayalam, a language spoken in India, has two rhotic sounds that have a retracted tongue root—the dark retroflex lateral and the trill (Scobie, Punnoose, & Khattab, 2013).

There is still not a clear understanding of the articulatory requirements of the posterior portions of the tongue for /ɾ/. With more detailed knowledge of the articulatory requirements for /ɾ/ we can develop better strategies that can target positioning of /ɾ/’s primary and possibly secondary constriction for individuals that have undergone treatment or formal instruction and are still exhibiting production errors with the rhotic segment. To address the limited information found in the literature, the authors of this paper want to answer the following research question: Does tongue configuration for /ɾ/ exhibits a retracted tongue root positioning similar to the English approximant?

Methods

Participants

Adult native Spanish speakers from different countries were recruited to participate. Participants were recruited by extending invitations to a Hispanic student association at the University of Cincinnati and some were recruited by word of mouth from individuals who participated from the study. The dialects represented in the data vary from Spanish dialects used
in the Americas (USA, Central and South America), Caribbean and Europe. Table 1 provides descriptive data from participants. All participants were able to read Spanish.

Table 1.

Spanish dialects represented in our data and number of speakers

<table>
<thead>
<tr>
<th>Spanish dialect</th>
<th>Number of speakers</th>
<th>Spanish dialect</th>
<th>Number of Speakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>4</td>
<td>Chile</td>
<td>1</td>
</tr>
<tr>
<td>Colombia</td>
<td>8</td>
<td>Venezuela</td>
<td>1</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>5</td>
<td>Argentina</td>
<td>1</td>
</tr>
<tr>
<td>Cuba</td>
<td>1</td>
<td>Spain</td>
<td>1</td>
</tr>
<tr>
<td>Tejano</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Trill stimuli

A word list was created with different Spanish words containing the target sound /r/ with different vowel context and at different positions (Appendix A). Due to the phonology of Spanish, trill production is limited to word-initial and intervocalic positions, and following certain consonants like /n/, /s/ and /l/ (Quillis and Fernandez, 1992; Lewis 2004; Lipski, 1994; Navarro-Tomas, 1996). Each participant was asked to read each word.

Equipment and Data Gathering Process

To capture tongue configuration for production of the Spanish trill, an Aloka SSD-1000 ultrasound machine with a 5MHz transducer (60mm radius, 60° field of view) probe was used. Audio recordings were made with the use of an Auditechnica AT2021 shotgun microphone. Both the ultrasound video and audio feeds were simultaneously recorded using a
VHS recording device with 29 frames per second. VHS recordings were then digitized to .avi format using a Sony SLV-D55OP or Panasonic DMR-E48V dual VHS-DVD units, a Behringer Xenyx 502 mixer, Gigaware VHS-to-DVD Video converter, Realtek High Definition Audio sound card and Debut Video Capture Profesional digitizing software. The audio was digitized at 16 bits and a sampling rate of 32 kHz.

The ultrasound transducer probe was positioned under the participant's jaw in order to capture a midsagittal image of the tongue. Participants manually held the ultrasound transducer probe during the experiment. To ensure adequate midsagittal image of the tongue, the participants were trained and instructed to maintain the ultrasound probe in a position that allowed imaging of the shadows casts by the mandible and hyoid bones. The field of view (60° field of view) allowed imaging of the area of the pharynx behind the hyoid bone. Participants were continuously monitored to ensure: (1) Ultrasound transducer was placed midsagittally placed under the participant's jaw. (2) Ultrasound imaging showed the shadows of the hyoid bone and mandible bones.

A subset of participants repeated the experiment using a system for head and ultrasound transducer stabilization. This system followed Stone's (2005) descriptions for stabilizing the ultrasound transducer probe and the head of the participant. A stand was made in order to rest the forehead and chin. This restricted movement of the head while allowing jaw movement for speaking. A device fixed to the frame of the stabilizer held the ultrasound transducer probe in place under the participant's jaw. The portion of the stand frame where the participant rested the chin and the ultrasound transducer was held could be adjusted to the height of the participant for better stabilization and control. To assess if there are differences in the accuracy of imaging
tongue root positioning with and without the use of the stabilization frame, video recordings of this subset of participants were compared between the two conditions.

Participants were instructed to read the stimulus list that was presented at eye level. Due to some Spanish dialects having multiple dialects being spoken by their users (i.e. Speakers of Puerto Rican Spanish differentiate between two dialects used in Puerto Rico, one dialect being considered more prestigious than the other) participants were not instructed to use any particular Spanish dialect. Data on trill production after the consonants /s/, /n/, and /l/ was only able to be gathered for a subset of participants.

To assess the presence of pharyngeal constriction, still pictures were taken by a phonetically trained clinician from every /r/ instance. Using Wavesurfer 1.8.5, the video and audio were able to be studied frame by frame. The presence of pharyngeal constriction was assessed by visually examining (frame by frame) movement of the tongue root into the pharyngeal area. Due to coarticulatory movements, more attention to tongue root positioning for /r/s was given in contexts of vowels that have a more forward tongue root positioning. A still picture of the tongue root configuration of /r/ was taken from the ultrasound frame that matched the center of the acoustic signal of the sound. These pictures were then rated by a second phonetically trained clinician—with experience working with the use of ultrasound imaging with English rhotics—as exhibiting pharyngeal constriction if the tongue root was relatively horizontal. To determine if presence of a retracted tongue root positioning for /r/ was consistent across examiners, 30% of the still pictures were randomly selected for analysis. Each rater individually rated the images while analyzing the same pictures. The percentage of agreement
for presence of a retracted tongue root positioning during /r/ production was 100%. Still pictures that exhibited unclear tongue root positioning due to what appeared to be artifact movement or loss on contact between jaw and ultrasound transducer were excluded from the analysis.

**Results**

**Tongue Configuration**

Configuration and positioning of most of the parts of the tongue can be obtained by ultrasound imaging. Due to limitation of ultrasound imaging, imaging of tongue tip is unavailable due to shadows casted by the mandible bone and air space under the tongue tip. Midsagittal still images showed elevation of the tongue blade, which suggests that tongue tip was also being elevated, most certainly towards the alveolar area. This configuration of the tongue tip and blade is what has been thoroughly described in the literature for /r/.

The particular imaging characteristics of the ultrasound transducer and the angle at which it is held under the tongue causes the surface of the tongue root to appear relatively horizontal on the screen when it is retracted toward the pharyngeal back wall. Ratings of the still pictures showed a retracted tongue root positioning for all instances were /r/ was produced, suggesting this is an intrinsic feature of the rhotic segment. No statistical analysis was needed due to presence of a retracted tongue root positioning on all instances.

Figures 1 through 6 show still images of Spanish trill being produced at the beginning of the word. Tongue root surface appears to be relative horizontal in word initial positioning with context of vowels that have a more forward tongue root positioning (Figures 1, 2, 4, and 5) as well as in the contexts of vowels that have a more retracted tongue root positioning (Figures 3
and 6). In Figures 2 and 5, an ultrasound image of /r/ in the word /riso/ shows a retracted tongue root. When compared—from the same participant—to the tongue root positioning of /i/, a more forward tongue root positioning is observed for the vowel. Similarly, differences are observed when tongue root positioning of /r/ and /u/ are compared (See Figure 1 and Figure 4) with /r/ showing a retracted tongue root while /u/ lacks a retracted tongue root. On contexts were the post-rhotic segment is a vowel that has a retracted tongue root, similar tongue root positioning is observed for both the rhotic /r/ and the post-rhotic vowel segment /a/. Figures 3 and 6 show a comparison of tongue root positioning for /r/ in the words /rawl/ and /rasa/ with tongue root configuration for the vowel segment /a/ for each speaker.

The same retracted tongue root positioning at word-initial /r/ is observed for the rhotic segment /r/ at intervocalic position. Figure 7 shows tongue root positioning of /r/ between /ero/ and /ara/ contexts in words like /sjero/ and /xara/ respectively. The mid-vowels /e/ and /o/ do not have a tongue root positioning as extreme as /a/, /i/, and /u/. That is, as forward as /i/ and /u/ or as retracted as /a/. However, it is plausible to think that although these vowels might not have an extreme tongue root positioning and vowels seem to have very limited effect on /r/ tongue root positioning, the rhotic segment /r/ maintains what it appears to be an intrinsic aspect of its articulatory requirements; a retracted tongue root positioning. On the last context studied, /r/ after consonants /n/, /s/, and /l/, ultrasound imaging reveals the same retracted tongue root positioning for the rhotic segment /r/ (See Figure 8). Data gathered on /r/ production after consonants /n/, /s/, and /l/ was limited for this study as only a small subset of participants were provided with Spanish words containing such context. However tongue root positioning continues to be retracted. The restrictive place of articulation for /r/ noted by the limited effect
vowels have on /r/'s tongue root positioning appears to also be maintained through other consonantal contexts.

Figure 1. Speaker from Puerto Rico. Tongue root configuration for word-initial trill /r/ (left) and vocalic segment /u/ (right) in the word /ruyoso/.
Figure 2. Speaker from Puerto Rico. Tongue root configuration for word-initial trill /r/ (left) and vocalic segment /i/ (right) in the word /riso/.

Figure 3. Speaker from Puerto Rico. Tongue root configuration for word-initial trill /r/ (left) and vocalic segment /a/ (right) in the word /rasa/.
Figure 4. Speaker from Chile. Tongue root configuration for word-initial trill /ɾ/ (left) and vocalic segment /u/ (right) in the word /ruʝoso/.

Figure 5. Speaker from Chile. Tongue root configuration for word-initial trill /ɾ/ (left) and vocalic segment /i/ (right) in the word /riso/.
Figure 6. Speaker from Chile. Tongue root configuration for word-initial trill /ɾ/ (left) and vocalic segment /a/ (right) in the word /rama/.

Figure 7
Speaker from Spain. Tongue root configuration for intervocalic trill /ɾ/ in /őjero/ (left) and /xara/ (right).

Figure 8. Speaker from Chile. Comparison of tongue root configuration for /ɾ/ after consonant /n/ in the word /onra/ (left), /ɾ/ after consonant /s/ in the word /israel/ (middle), and /ɾ/ after consonant /l/ in the word /alredeðoɾ/(right).
To study if tongue configuration for the apicoalveolar trill /r/ showed a retracted tongue root as the one observed for the English approximant, ultrasound imaging technology was used on adult native speakers of various Spanish dialects. To better understand the articulatory requirements of /r/ at the posterior portions of the tongue, we focused on analyzing tongue root positioning of /r/ productions in different contexts and word positioning. Our data shed some clarification on what previous work have vaguely suggested but was still unclear. That is, /r/ tongue configuration is characterized by having a retracted tongue root positioning. Although ultrasound imaging data does not provide information about the area of the pharynx, a retracted tongue root would create a narrowing of the vocal tract tube at the level of the pharynx, creating a constriction. The degree of the pharyngeal constriction, that is, the relative approximation between the tongue root towards the back wall of the pharynx, is unclear.

Figure 9. Speaker from Chile. Comparison of tongue root configuration for word-initial trill /r/ using a head stabilizer (left) and without using a head stabilizer (right) in the word /riso/. 
A retracted tongue root has been noted on different rhotic productions across languages. From these rhotics with a retracted tongue root, there was limited information if /r/ is part of this pharyngealized rhotic group. Previously, an attempt to include /r/ in this group was made by Magnuson (2007) but there was a lack of empirical and imaging data that provided evidence of a co-occurring secondary place of articulation for /r/ just like the one observed for the English approximant /ɹ/. Our data gathered from native speakers of various Spanish dialects provides more of these required data in order to consider /r/ as a member of the pharyngealized rhotics group.

The complexity of /r/’s primary constriction has already been well established by previous authors but it appears that the articulatory complexity of /r/ goes beyond its primary constriction. While the anterior portions of the tongue move forward and up towards the alveolar region, the posterior portion of the tongue—the tongue root—must move back towards the back pharyngeal wall. This articulatory complexity of /r/—the two co-occurring constrictions and precise aerodynamics—could explain why this rhotic segment is challenging to master for many learners.

**Role of pharyngeal constriction of /r/**

Unlike our understanding of the need of a retracted tongue root to create a pharyngeal constriction for the English approximant, the need for a retracted tongue root to create a pharyngeal constriction for the production of /r/ is not well understood. For the English approximant, the pharyngeal constriction aids in lowering the third formant of the acoustic profile of sound, which is a reliable acoustic correlate trademark of the English approximant /ɹ/ (Zhou, et. al, 2008) as well as an important part of its acoustic profile for accurate perceptual
identification of the sound (Hamilton, Ishikawa, Mullins, & Boyce, 2015). Regarding /r/, it is not clear if this constriction at the level of the pharynx is needed in order to create important acoustic information for native speakers to accurately identify the sound besides—or in conjunction—to the more salient aspect of /r/’s acoustical profile, the trilling.

The presence of a retracted tongue root positioning for /r/ might be closely related to how the sequential and rapid constrictions at the alveolar region are made. A retracted tongue root positioning could be what allows speakers to anchor and stabilize the tongue body. Once the tongue body is anchored and stabled, the more flaccid tongue tip and blade—or lateral sides of the tongue if an alternate tongue configuration is made (Rivera-Campos & Boyce, 2013)—can be put into a vibratory state. If tongue body is not stable, it might be more challenging to have the parts of the tongue used for trilling, initiated and maintain the rapid and consecutive constrictions.

Clinical implications

Professionals rely on what is known about the articulatory requirements of speech sounds in order to develop strategies that promote acquisition and mastery of speech sound production. In the case of /r/, this later development speech sound is characterized by having co-occurring places of constrictions. The primary constriction at the level of the alveolar region and a secondary constriction at the level of the pharynx characterized by a retracted tongue root. Solé (2002) described /r/ as having a restrictive place of articulation along the vocal tract and the presence of a retracted tongue root might explain Solé’s observation. A speech sound with co-occurring places of articulation, one primary and one secondary, requires that attention is given to both places of articulation. In the case of /r/, due articulatory descriptions mainly focusing
only on the primary constriction more attention should be provided to tongue root positioning when teaching acquisition and mastery of /r/. This is especially important for languages that retain the canonical production of /r/ or dialects that differentiated between less and more prestigious dialectal forms which are sometimes demarcated by how certain speech sounds are produced.

As presented before, /r/ is used across many languages of the world. Although our gathered data was by native speakers of Spanish producing /r/ in various contexts, descriptions across languages of the primary constriction of /r/ are mostly parallel (Ladefoged & Maddieson, 1996). In light of our data, it is plausible to think that across languages that use /r/ as part of their sound inventory a retracted tongue root positioning could be observed for /r/ production. This can allow for the development of articulatory strategies that can be used across languages for individuals who have yet to acquire and master production of /r/ as well as individuals or are learning /r/ due to learning a second language such as Persian, Spanish, Russian, and Italian just to mention a few.
Rhotic sounds are among the last sounds to achieve acquisition and mastery by children (Boyce, Hamilton & Rivera-Campos, 2016; McLoud, 2007) as well as individuals who are learning a second language (Gonzales-Bueno, 2005). Although children are expected to master production of rhotics without formal instruction, some children fail to meet this expectation. In such cases, these children are referred to practitioners for formal instructions aimed at ameliorating their errors. Just like children who have been referred to practitioners, individuals learning a second language are also provided with formal instruction for rhotic sounds not shared between their primary and secondary languages. However, even after formal instruction, some children and second language learners fail to acquire production. In the case of /r/, practitioners have limited information about best practices that can effectively be incorporated into teaching production of the rhotic sound.

Individuals who are learning a second language can occasionally face the challenge of needing to learn speech sounds that are not found in their primary language. In such cases, learners are commonly provided with formal instruction on how to produce such sounds as achieving adequate sound production is important to convey the desired meaning. Furthermore, the number of professionals who regularly communicate in a foreign language for their work or studies increases due to globalization, and adequate production of speech sounds is important for good speech intelligibility. In Spanish, native speakers differentiate between /ɾ/ and /r/ at intervocalic position to differentiate meaning. For example, /karó/ (expensive) and /karó/ (car).
In addition to this differentiation, many native speakers of Spanish consider accurate production of /r/ a prestige marker of speech and regard other Spanish dialects were /r/ production has allophonic variations as less formal (Zentella, 1987). To teach /r/ production, practitioners commonly use approaches that are based on our current knowledge of /r/’s salient aspect, the trilling. However, even after formal instruction, some second languages learners of Spanish continue to fail acquisition and accurate production. The main focus on trilling and overlooking other aspects of tongue configuration can limit the availability of best clinical practices that can be used for teaching /r/ especially for individuals that might require strategies that go beyond positioning the frontal parts of the tongue to achieve trilling.

The current work will explore the practice of using imaging technology such as ultrasound as well as additional potential facilitative strategies for teaching /r/ in an attempt to introduce additional best practices for practitioners to use. Ultrasound imaging technology will provide live information about placement of the various parts of the tongue for /r/ production which will be used for precise and individualized feedback that targets inaccurate tongue part placement. Teaching strategies that incorporate the previous aforementioned conditions: (1) voicing of the rhotic segment, (2) vowel contexts, (3) position of /r/ in the word, and (4) a retracted tongue root, will be used to teach production of /r/.

Current State of Knowledge Concerning Articulatory Requirements of /r/

Traditionally, teaching production of trill is based on phonetic knowledge. Our current phonetic knowledge describes how this rhotic consonantal sound possesses a complex tongue configuration characterized by (1) a primary at the level of the alveolar region (Ladefoged and Maddierson, 1996; Navarro-Tomas, 1996), (2) a likely secondary constriction at the level of the pharynx made by a retracted tongue root positioning (Boyce et al., 2016), and (3) precise
USING ULTRASOUND IMAGING FOR BETTER UNDERSTANDING

aerodynamics for trilling (Solé, 2002). In the literature, descriptions of the articulation of /r/ describe the tongue tip as being the tongue section that is put into a vibratory state (Ladefoged & Maddieson, 1996; Navarro-Tomas, 1996). However, some individuals exhibit an alternate configuration for /r/ in which one lateral edge of the tongue is used to vibrate while the other is anchored to the side of the teeth. (Rivera-Campos & Boyce, 2013a). For /r/ productions that use the tongue tip for vibration, the primary constriction location is at the more posterior portion of the alveolus (Recacens & Pallarès, 1999). For the individuals who use one lateral side of tongue, lingual palatal contact information is not clear.

The characteristic vibratory state during production of /r/ is considered to be driven by the same mechanics that drive vibration of the vocal folds, the Bernoulli Effect (Martinez-Celdrán, 1997). To initiate trilling, air from the lungs is channeled along the tongue by bracing (sic) the lateral sides of the tongue against the teeth (McGowan, 2002) and a total occlusion of the air passage is made by a linguopalatal constriction—by tongue tip—followed by an increase in the intraoral pressure. The part of the tongue used for blocking the air passage has to be flaccid enough to be pushed by the increasing intraoral pressure as well as to maintain trilling once the Bernoulli effect takes place. This cycle keeps repeating until intraoral pressure is no longer sufficient to maintain the trilling. For the secondary constriction of /r/, a retracted tongue root that approaches the back wall of the pharynx is required (Boyce et al., 2016; Rivera-Campos & Boyce, 2013). Information about /r/’s secondary constriction is relatively recent and seldom sources of information include this secondary constriction in their descriptions of /r/ production.

Teaching Acquisition of the Apicoalveolar Trill

Amelioration of Trill errors in children. The apicoalveolar trill is considered the last sound to be mastered by children who are monolingual speakers of Spanish (Jimenez, 1987;
Bosch, 1983; McCloud, 2007); with many children exhibiting mastery by age 7 (Bosch-Galceran, 2005). However, some children continue to exhibit speech errors past the expected mastery age. Commonly, this group of children with continued speech errors are referred to professionals who assess their speech sound productions and provide treatment that aims at ameliorating their errors by engaging the child into repeated oral practice (Bosch, 2005; Gonzalez-Bueno, 2005; Remache-Guastay, 2015). Usually these approaches can be implemented without the need to use complex instruments or expensive technology, making them ideal for many clinicians.

**Teaching Approaches used with children.** Commonly, teaching approaches used with children are complemented by (1) providing the child with a general articulatory description of how /r/ is articulated and (2) use of non-speech oral motor exercises. The information provided to children mainly focus on the primary constriction by teaching positioning of tongue tip and blade (e.g. Remache-Guastay, 2015). Non-speech oral motor exercises are used to practice relaxation of bucofacial muscles, increasing coordination and strength of face and tongue muscles, and control of airflow from lungs. Although attempts to disseminate research information regarding the negligible efficacy of non-speech oral motor exercises in Spanish literature has been achieved by some authors like Ygual-Fernández, Cervera-Mérida (2016) non-speech oral exercises are still being used and promoted by professionals who work with Spanish speaking children (e.g. Choco-Guamán & Merchán-Lapo 2012; Yagual-Bazan & Tomala-Chavaria, 2013; Soriano-Pozo & Tomala-Chavarria, 2013). Use of strategies that have failed to provide evidence that support speech sound acquisition have great potential to overtake opportunities to use strategies that could better benefit learning of the target sound. Perhaps the continued use of non-speech oral exercises bourns from the limited amount of best clinical
practices that practitioners can find in the literature were their incorporation requires little to no technology. As such strategies are of great appeal to practitioners that service individual at cites with limited resources and access to more modern equipment. The need to reduce the gap of available best practices for teaching /r/ that can be easily applied is significant as practitioners need more options to more efficiently teach /r/.

Practitioners at cites with easier access to more modern technologies, strategies that provide biofeedback are more common. This biofeedback is used to teach awareness of tongue configuration used when attempting production of the target sound. Learners have a more guided approach on how to position certain parts of the tongue and what changes in tongue configuration are needed for accurate production. These technologies include ultrasound imaging (Adler-Bock, Bernhardt, Gick, & Bacsfalvi, 2007; Preston, Brick, & Landi, 2013, Preston et al., 2015; Modha, Bernhardt, Church & Bacsvalvi, 2008), palatography (Dagenais, 1995; Gibbon, Stewart, Hardcastle, & Crampin, 1999), and spectral biofeedback (Byun, & Hitchcock, 2012; Shuster, Ruscello & Toth, 1995). Many of these technologies have been used to target production errors with the English rhotic approximant /ɹ/ with positive results (e.g. Preston et al., 2014; Preston et al., 2013; Adler-Bock et al., 2007). From these aforementioned technologies, ultrasound imaging appears to allow for a great level of monitoring correct positioning of various parts of the tongue (i.e. tongue root, dorsum, blade and lateral sides) when compared to the rest of these technologies. This is especially helpful for teaching rhotics sounds with complex articulatory requirements like /ɹ/, /ʁ/, and /ʂ/ (Boyce et al., 2016). Additionally, it allows usage by multiple users as it does not require to be individualized with prosthetics for each user and is minimally invasive, as opposed to palatography.
Research information describing the effectiveness of ultrasound imaging technology for teaching production of /r/ is greatly limited. Interestingly, this technology appears to have potential for teaching /r/ as this rhotic appears to share a complex articulatory requirement just like the English approximant /ɹ/ as noted by Boyce, et al., (2016) as well live information of placement of tongue blade, dorsum, root and lateral sides when attempting /r/ production. More knowledge on the use of this technology can allow for better teaching strategies in cites with better access to resources. As ultrasound imaging becomes cheaper and more mobile, more readily access can be provided to practitioners servicing children in areas limited resources.

**Teaching production of the apicoalveolar trill to second language learners of Spanish.** When learning a second language, individuals can face the challenge of needing to learn a sound that might not be used on their primary language. Learning to achieve /r/’s primary constriction can make it more challenging for second language learners with a primary language that does not use /r/. The challenging nature of /r/ acquisition could be the need to acquire and master a new articulatory movement—the multiple and fast constrictions created by aerodynamics—for a sound that is not used in their language as opposed to learning a sound that does not require learning of new articulatory movements (Waltmunson, 2005). This has been observed by Face (2006) and Johnson (2008) in primary speakers of English where acquisition of /r/ appears to follow phases that demark progress in acquisition. These phases range from substitution of /r/ for another sound, substitution of /r/ for tap /ɾ/—another rhotic sound used in Spanish and used in some English dialects as an allophone of /t/ and /d/ in intervocalic position, shares similar place of articulation as the apicoalveolar trill—and attaining /r/ production as the last phase (Johnson, 2008). Additionally, productions of /r/ by second language learners appear
to also follow a continuum of progress where acoustically, /r/ production become more similar to the acoustic pattern of a native speaker’s /r/ (Johnson, 2008).

Tongue configuration used for /ɹ/ by a native speaker of English could increase or decrease the amount of learning of new articulatory gestures needed for /r/ acquisition. As speakers from North American English use a wide variety of tongue configuration for production to /ɹ/, some tongue configurations appear to have a positioning of tongue root, blade and tip similar to what has been described for /r/. Tiede, Boyce, Holland, and Choe, (2004) present a tongue configuration continuum for /ɹ/ after using magnetic resonance imaging of tongue configuration of native speakers of North American English producing the rhotic. On one end of the continuum, tongue configurations are classified as bunched with a lowered tongue tip and tongue configurations at the opposite end being classified as retroflex. From this continuum, tongue configuration that look more similar to what has been described for /r/ are the retroflex shapes. Olsen (2012) suggested that retroflex tongue configuration for the English approximant /ɹ/ can facilitate acquisition of /r/ when compared to bunched tongue configurations. However, data visual inspection of data from Tiede et al. (2004), bunched tongue configurations appear to be more frequent than retroflex. A more limited number of retroflex tongue configuration could suggest that many speakers of North American English could have a more challenging experience for learning /r/. However, some speakers change tongue configurations depending on vowel contexts (Zhou, Espy-Wilson, Boyce, Tiede, Holland & Choe, 2008). That is, on certain contexts a speaker might use a particular tongue configuration for /ɹ/ while on other contexts the same speaker could use a different tongue configuration for the same rhotic sound. A speaker that changes from a bunched to a retroflex tongue shape on certain contexts could potentially
need to learn less new articulatory movements for /r/ when compared to someone who maintains or changes between two or more bunched tongue shapes.

Teaching approaches used for second language learners. At the college level, teaching /r/ is popularly approached by providing the learner auditory models and formal instruction on how to achieve production. During formal instruction, it is common practice to use sources like textbooks, animations, diagrams and recorded speech to guide the learners (e.g. Lord, 2005; Hurtado & Estrada, 2010; Añorga & Benander, 2015; Kissling 2013) with some teaching practices using spectographic imaging displays (e.g. Herd, 2011). Review of the some of the sources used on these works provide descriptions that only focus on the primary constriction of the rhotic segment. Additionally, review of the animation sources also show articulatory inaccuracies. For example, the primary constriction is shown as very forward along the alveolar region and there is no indication of a secondary constriction at the level of the pharynx. Although most of the authors reported an increase in accuracy production of /r/, there were participants who attained limited proficiency in /r/ production and others did not acquire the sound. Due to the nature of most of the information sources and the approaches used on these aforementioned studies, it is plausible to think that many of the learners were not provided with information about what changes were needed in their tongue configurations for proper /r/ production. This in turn can make acquisition and mastery of /r/ a more challenging task for learners who appeared to not benefit from formal instruction as much as the learners who were able to achieve /r/ production.

By using spectographic displays, Herd (2011) reports that production of /r/ increased in native speakers of English who were learning Spanish as a second language. However, the production piece of Herd’s (2011) approach had no guided instructions on how to articulate /r/ as
participants were only presented with a waveform and spectrogram image of a native Spanish speaker’s /r/ production and asked to match their attempt at producing /r/ with what was presented. Potential challenges that learners of Spanish might have faced with the way Herd (2011) approached the production aspect for teaching /r/ are: (a) interpreting a waveform or spectographic displays is not intuitive for the average person and requires training. (2) waveform and spectographic displays are abstract images of tongue configuration and (3) there is no simple correspondence between tongue configuration and the acoustic signal (Neri, A, Cucchiarini, Strik, H, & Boves, L. (2002). Additionally, learners are forced to identify—albeit with a high degree of uncertainty—what changes were needed in their tongue configuration in order to match the provided acoustic profile.

Achieving accurate production of /r/ can be of most importance for individuals that pursue a more native like pronunciation of their second language. Although speech with a foreign accent can have a minor impact in speech intelligibility, some native listeners can negatively judge foreign accented speech as a general intolerance for strong foreign accent has been described in previous studies (Derwing & Murno, 2009; Brennan & Brennan 1981, Morley 1991). In the case of Spanish and adequate /r/ productions, some dialects differentiate between prestige and less prestige versions of Spanish depending on how /r/ is produced (Zentella, 1987).

**Potential Facilitative Contexts to Teach Acquisition of /r/**

The articulatory research literature provides some suggestions for conditions that can provide better production accuracy for /r/. (1) devoicing of the segment, (2) vowel contexts, (3) position of /r/ in the word, and (4) tensing of the tongue at a particular point along its length. These are not mentioned in the literature on formal training for /r/ production.
Devoicing of the rhotic segment. To facilitate acquisition of /r/, it has been recommended to practice production of the rhotic as a devoiced segment (Teschner, 2002). In a study by Solé (2002) voiced /r/ was observed to have: (1) lower intraoral pressures for initiation and maintenance of trilling (2) Due to being less robust to changes in pressures, voiced /r/ possesses a more limited range of acceptable intraoral pressures for its production. On the other hand, Solé (2002) reported that voiceless /r/ requires: (1) higher levels of intraoral pressure for trill initiation and maintenance and (2) as being more robust to changing pressure, voiceless /r/ possesses a more wider range of acceptable intraoral pressures for its production. These differences between these two allophonic variations of /r/ suggests that voiceless trills could present less difficulties for production. Different phonation patterns—voicing or devoicing—of /r/ has been observed in Spanish. Lewis (2004) reported that native speakers of Spanish often produce a devoiced /r/ when the rhotic segment is preceded by a voiceless segment. On the other hand, Rivera-Campos and DeMott (2016) found that native speakers of Spanish often produce a voiced /r/ when the rhotic segment is preceded by a voiceless segment. These different phonation patterns appear to make uncertain if voicing or devoicing the rhotic segments could be a facilitative context that can be used for teaching production of /r/. However, the observations by Solé (2002) and Lewis (2002) seem to fit together with might native speakers of Spanish do in conversational speech and thus providing us with a potential strategy to teaching production of /r/.

Vowel contexts. By studying production accuracy of /r/ by second language learners, Waltmunson (2005) observed higher accuracy scores for the rhotic segment in certain vowel contexts. In his research, the author reported that almost all participants had higher scores on /r/ productions in the contexts with low vowel contexts (i.e. /a/, /o/) while accuracy of /r/ in high vowel contexts (i.e. /u/, /i/) showed the lowest accuracy scores. The higher accuracy scores for
/r/ production on contexts reported by Waltmunson (2005) could be related to articulatory similarities shared between the rhotic segment and vowels like /a/. Ultrasound imaging data comparison of various rhotics and vowels by Boyce, Hamilton and Rivera-Campos (2016) show a similar retracted tongue root positioning for /r/ and /a/ segments.

**Positioning of /r/ in a word.** Positioning of the rhotic segment in a word appears to have an effect on its mastery and acquisition. Reports from various studies have observed that production accuracy of /r/ by second language learners of Spanish is lowered when the rhotic segment is at intervocalic position and lowered when it is located at word-initial position (e.g. Johnson, 2008; Waltmunson, 2005; Hurtado & Estrada, 2010). Furthermore, accurate production of /r/ is seem to be acquired sooner at intervocalic positions when compared to word-initial (Johnson, 2008).

**Tensing of the tongue at a particular point along its length.** Johnson (2008) states that /r/ can inevitably (sic) be produced once the commonly known articulatory requirements are met (airflow, intraoral pressure, apicoalveolar constriction) in combination with what he refers as “muscular tensing of the tongue at a particular point along its length”. Although he does not provide details about the location of the muscular tension along the tongue, it is plausible that this tensing is occurring at the tongue root as it move towards the back wall of the pharynx to create a constriction (Boyce, Hamilton & Rivera-Campos, 2016). This tongue root movement might work as a way to anchor the tongue—hence being the point of most tension—in order to facilitate a more relaxed tongue tip and blade for trilling.

The present research aimed to provide a tutorial for practitioners concerning instructional strategies that can more effectively support acquisition of /r/ using ultrasound technology and various facilitative contexts. This research intended to answer the following question: Does the
use of various facilitative contexts (devoicing of /r/, vowel contexts, position of /r/ in the word, and retracted tongue root positioning) and ultrasound imaging for tongue configuration monitoring potential practices for facilitate the acquisition of the apicoalveolar trill /r/ in second language learners of Spanish? The findings will address the gaps in the literature regarding the potential use of ultrasound as a teaching tool for /r/ as well as expand the current number of strategies that practitioners can apply for promoting acquisition of /r/.

Methods

Participants

Eight adult native speakers of English that were interested in acquiring production of /r/ were recruited in this study. Six participants had a background of learning Spanish as a second language while two participants had no background of learning Spanish as a second language. One participant decided to terminate participation in the study before all training sessions were provided due to availability constraints. Only results from participants who completed the training program were included in the analysis.

Initial and Final Assessments

A list of fifty-four (54) Spanish words containing /r/ at different word positions and vowel contexts was developed and administered to all participants before all training sessions were provided. Word positions included word-initial, intervocalic, and after consonants /s/, /l/, and /n/. Simultaneous audio and ultrasound imaging recordings were made while participants read at eye-level the developed word list. In order to qualify for participation in the present study, production accuracy score of /r/ was required to be equal or less than 20%. Productions of /r/ were perceptually judged by a native speaker of Spanish who rated participant’s production as accurate or inaccurate. Only canonical productions of /r/ were rated as accurate while allophonic
and non-canonical productions of /r/ were rated as inaccurate. A binomial scoring system was used for the assessments. If the participant produced an accurate /r/ during the reading of the target word, a score of 1 was given. An error production scored 0 points. This assessment was repeated once more all training sessions were provided to the participant.

**Equipment for Data Collection Process**

To capture tongue configuration for production of the Spanish trill, a Siemens Acuson X300 Premium Edition Diagnostic Ultrasound System with a C6-2 (4.0 MHz) curved array transducer was used. Ultrasound settings allowed for 36 fps and a dynamic range of 55dB. Transducer depth was 8cm. Video recordings were made with the use of AVerMedia C127 Extreme PCIe HD Capture software and Audiotechnica microphone. The ultrasound transducer probe was positioned under the participant's jaw in order to capture a midsagittal image of the tongue. Participants manually held the ultrasound transducer probe during the sessions. To ensure adequate midsagittal image of the tongue, the participants were trained and instructed to maintain the ultrasound probe in a position that allowed imaging of the shadows casted by the mandible and hyoid bones as this are landmarks that can be used to monitor if transducer is imaging too forward or too far back along the vocal tract. The ultrasound transducer allowed imaging of the area of the pharynx behind the hyoid bone. Participants were continuously monitored to ensure: (1) Ultrasound transducer was placed midsagittally under the participant's jaw. (2) Ultrasound imaging showed the shadows of the hyoid bone and mandible bones.

**Overview of the Training Program**

Teaching production of /r/ was provided during a training period of six sessions with each session lasting 30 minutes. Participants were randomly assigned to two different training groups. One group received training on word-initial /r/ while the other group received training for
intervocalic /r/. All training sessions commenced with the administration of two short daily probe lists followed by the use of a structured protocol similar to the one used by (Preston et al., 2014) to practice production of /r/. Once all training sessions concluded, the same initial assessment used for /r/ accuracy was administered as a final assessment. Appendix A shows the words used for initial and final assessment.

**Daily Probes for Monitoring Progress**

To monitor progress over time on trained and untrained contexts, two probe lists consisting of 15 words—each focusing on one variant of /r/—were used. Both probes were administered before commencing every training session. Due to the limited number of Spanish words where /r/ is preceded by consonants /s/, /n/ and /l/, these contexts were not monitored with daily probes. Same scoring system for assessments were used for scoring daily probes. Appendix B shows the words used for word-initial and intervocalic /r/ probes.

**Training Protocol**

All training sessions were structured by means of a protocol. The protocol used for the present work was a modified version of the structured protocol used by Preston et al (2014), to teach English approximant to children who had residual speech sound errors. This protocol allowed for structured practice, allowing the learner to move through levels that increase in complexity as he or she masters /r/ production and allowed the clinician to provide more feedback at early levels of /r/ acquisition and less feedback as the individual mastered /r/ production. The modifications to the structured protocol used in the present study were needed in order to account for the phonological differences between Spanish and English and to allow the clinician to use both midsagittal (for monitoring positioning of tongue blade, dorsum and
root) and coronal (for monitoring of lateral sides of tongue) views when training tongue configuration for Spanish trill.

The protocol was structured to provide the participant with methods to practice shaping of tongue configuration for adequate /r/ production as well as to provide structured practice using Spanish words. The protocol also included two specific types of feedback; knowledge of performance (KP) and knowledge of results (KR). KP feedback focused on the performance of the task while KR focused on judgements of incorrect or incorrect production of /r/. Participants were allowed to move to structured practice using Spanish words once he or she was to produce 5 perceptually correct Spanish /r/’s. In order to produce these 5 correct trills, various strategies that promoted shaping of the tongue configuration for adequate positioning of tongue blade, dorsum, root and lateral sides of the tongue were used. These strategies for shaping /r/ also included some the aforementioned potential contexts for /r/ acquisition (i.e. devoicing of the segment by shaping /r/ from /s/, /lv/, and /ʃ/, shaping /r/ from various vowel contexts) as other contexts (i.e. positioning of /r/ in the word) were exclusively used with participants who were assigned to learn /r/ using one of two variants (word-initial or intervocalic). After the participant produced 5 adequate trills (they did not need to be consecutive) the structured practice commenced by targeting the selected variant of /r/ with two different vowel contexts. The selected vowel contexts were randomly selected from the vowel contexts that showed less accuracy during the initial assessment of /r/. For example, if the variant of word initial /r/ was targeted and the initial /r/ assessment showed that participant had no accuracy of /r/ in /ra/ and /ru/, those two vowel contexts were be targeted during the training session of word initial /r/.

Each vowel context was used to provide opportunities to practice the targeted variant of /r/ through a series of levels that increased in difficulty as the participant mastered the /r/ at each
level. The incrementing difficulty levels word initial position were: simple syllable (i.e. /ra/, /re/), two syllable words (/rama/, /reto/), three syllable word (i.e. /rafayə/, /remoto/), and cloze phrase (i.e. /rafayadebil/, /remotopajs/). The incrementing difficulty levels for intervocalic position were shared with the ones used for word-initial with exception of simple syllable, which was replaced for VCV stimulus (i.e. /ara/, /iri/). Each level provided five instances for practice with opportunities for the clinician to provide different feedback. For example, after an attempt of producing /r/, the clinician provided feedback regarding position of the tongue dorsum (KP feedback) while feedback about perceptual identification of a correct or incorrect /r/ is KR. As the participant progressed through the difficult levels the amount of KP and KR diminished in order to promote learning and automonitoring skills. In order for a participant to move from one level to the next (i.e. from the simple syllable to two syllable words) the participant needed to produce and adequate perceptual /r/, using the context being practiced, a minimum of 4 times out of the 5 opportunities. If the participant failed to achieve this minimum requirement, he or she will be dropped down to the lowest level to continue practice. Words used during the assessments and daily probes were not used for practice during structured practice.

Results

Table 1 shows trained and untrained /r/ context by participant. Initial and final assessment raw scores of accurate trill production by contexts for each participant are shown in Figure 1. Participants B, C, E, and G showed improvement in acquisition of /r/ after all training sessions were provided.
Table 1
Trained and Untrained /r/ Contexts by Participants

<table>
<thead>
<tr>
<th>Participants</th>
<th>Trained context</th>
<th>Untrained context</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant A</td>
<td>Intervocalic</td>
<td>Word-initial and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant B</td>
<td>Intervocalic</td>
<td>Word-initial and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant C</td>
<td>Word-Initial</td>
<td>Intervocalic and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant D</td>
<td>Word-initial</td>
<td>Intervocalic and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant E</td>
<td>Intervocalic</td>
<td>Word-initial and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant F</td>
<td>Word-Initial</td>
<td>Intervocalic and after consonants /s/, /n/, and /l/.</td>
</tr>
<tr>
<td>Participant G</td>
<td>Intervocalic</td>
<td>Word-initial and after consonants /s/, /n/, and /l/.</td>
</tr>
</tbody>
</table>

Figures 2 through 8 show participants’ raw scores on daily word probes for accurate /r/ productions on trained and untrained /r/ contexts. Participants B, C, E, and G showed trill acquisition in both trained and untrained contexts. This tentatively suggests that learners can generalize to untrained contexts once acquisition is achieved.

Figure 1. Participant’s Raw Accuracy Scores for /r/ During Initial and Final Assessments of /r/ by Contexts.
**Figure 2.** Participant A’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

![Participant A's raw score for accurate /r/ production on daily probes](image1)

**Figure 3.** Participant B’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

![Participant B's raw score for accurate /r/ production on daily probes](image2)
**Figure 4.** Participant C’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

![Participant C's raw score for accurate /r/ production on daily probes](image)

**Figure 5.** Participant D’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

![Participant D's raw score for accurate /r/ production on daily probes](image)
Figure 6. Participant E’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

Figure 7. Participant F’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.


**Figure 8.** Participant G’s raw accuracy productions of /r/ over a period of six training sessions on trained and untrained contexts.

Devoicing of the rhotic segment. During training, all participants were instructed to devoice the rhotic segment when attempting to produce /r/. This was done as a strategy to promote initiation and maintenance of trilling as voiceless /r/ might be easier to produce due to their wider range of adequate intraoral pressures for their production. Clinical notes taken during the training sessions of each participant reported limited success for facilitating initiation and maintenance of trilling by devoicing the segment with some participants reporting that it felt unnatural or more difficult to trill. Interestingly, if voicing of the rhotic segment was used, clinical notes reported more instances of successful initial acquisition of /r/.

Vowel contexts, positioning of /r/ in a word, and tongue root retraction. These strategies appear to work in tandem for acquisition of /r/. A low-back vowel context seemed to be a facilitator for acquisition of the rhotic segment at word-initial and intervocalic positions (i.e. /a/). However, intervocalic position seemed to better benefit from this context when compared to
word-initial position. This can be seen as the number of participants who presented acquisition /r/ and received word-initial training (Participant C) are less when compared to the number of participants who presented acquisition of /r/ and received intervocalic training (Participants B, E, and G). From the clinical notes, it was found that for participants who were trained in the intervocalic position, a low-back vowel context that provided more accurate /r/ productions was /ara/. Vowel contexts such as /i/ and /u/ provided the least accuracy for /r/ productions in both variants of /r/. A possible explanation for this might be the positioning of the tongue root for these vowels as presented on ultrasound imaging work by Boyce, Hamilton and Rivera-Campos (2016). The authors show that for both /i/ and /u/, tongue root positioning is more forward along the vocal tract when compared to tongue root positioning for /r/. It might be plausible to think that these differences in tongue root positioning might be what affects /r/ accuracy production for individuals who are learning how to produce the segment when it is embedded in /u/ or /i/ contexts. To produce /r/ in these two vowel contexts, the individual will need to change tongue root positioning—from back to front or front to back—which might be a challenging task when initially learning how to produce /r/.

*Use of ultrasound to monitor tongue configuration.* The use of ultrasound allowed for individualized feedback targeting positioning of the various parts of the tongue during accurate and inaccurate /r/ productions. In accurate tongue part positioning, feedback was used to discuss changes that participant might have made from previous error tongue shapes or make the participant aware of accurate placements that are being maintained. In inaccurate tongue part positioning, feedback was used to discuss changes in tongue part positioning that are needed in order to achieve accurate placement. As participants went further into the training sessions, they demonstrated a level of self-awareness related to tongue configuration while looking at the
ultrasound monitor. They would sometimes spontaneously mention what accuracies and inaccuracies in tongue part placement they observed on their tongue shape after attempting production of /r/. Ultrasound imaging was particularly helpful for monitoring positioning of the tongue root and lateral sides of the tongue. With the use of the ultrasound, it was possible to bring and maintain attention to this portion of the tongue during the training sessions as a retracted tongue root is needed for /r/ production (Boyce, Hamilton and Rivera-Campos, 2016). Being able to monitoring positioning of this far back portion of the tongue relates to one of the conditions that seem to promote production of /r/, tensing of the tongue at a particular tongue along its length. With the use of ultrasound, monitoring tongue root positioning can be easily accomplished as this section of the tongue is located far back along the vocal tract and can be challenging to monitor without imaging technologies.

Coronal imaging of the tongue provided information about positioning of the lateral sides which provided information if participant had one or both sides lowered. Having raised lateral sides of tongue allows for channeling airflow to initiate tongue tip trilling (Mc Gowan, 1992; Navarro Tomas, 1996)—or in the case of some native speakers of Spanish—lateral trilling (Rivera-Campos and Boyce, 2013a). Interestingly, Participant G achieved production of /r/ by using this alternate tongue configuration, lateral trilling (See Figure 9). Still picture from video shows one side of the tongue slightly lowered when compared to the opposite side. When video is observed, the slightly lowered side shows oscillatory movements when trilling. For Participant G, lateral tongue side raising was something that was mostly the focus during training as one or both sides were commonly lowered producing an inaccurate /r/ (See Figure 10). Contrary to participant F, one lateral side of the tongue for Participant G is much lowered and trilling was not produced. This lowering of one side allowed air to escape without facilitating trilling. As with
tongue root positioning, monitoring lateral sides of tongue was easily accomplished by using ultrasound.

**Figure 9.** Still image of Participant G’s coronal view of alternate tongue configuration for trilling. Slightly lowered left lateral side of tongue is used for trilling.

**Figure 10.** Participant F’s coronal view of tongue showing lateral left side of tongue lowered allowing air flow to escape.
Discussion

This work intended to explore best practices for teaching production of /r/ by incorporating the use of ultrasound imaging technology and the use of teaching strategies that have a potential to facilitate /r/ acquisition. Ultrasound imaging technology allowed for live information about the placements of various parts of the tongue which was used for provide precise feedback about tongue part placement. Teaching strategies that provided the best outcomes for acquisition of /r/ were (1) voicing of the rhotic segment, (2) use of low-back vowel contexts for facilitate a retracted tongue root positioning, (3) use intervocalic position of /r/,

However, it is important to note that imaging tongue configuration for /r/ using ultrasound has some limitations. The frontal section of the hard palate cannot be imaged using ultrasound as the soundwaves emitted from the ultrasound probe cast a shadow over the alveolar region as well as the tongue tip and part of the tongue blade. This shadow is created by the soundwaves emitted from the ultrasound transducer probe when the waves encounter: (1) the mandible bone and (2) airspace below the tongue tip when raised. Not having information about the positioning of the apicoalveolar constriction limits awareness if the primary constriction is being attempted too far forward along the alveolar region.

Overall, the strategies used in this work have shed some light in the area of best practices for teaching acquisition of /r/. A teaching approach that targets acquisition of /r/ should include a modality that allows for the practitioner and the learner of /r/ to have information about positioning of the different parts of the tongue when attempting /r/. This information is crucial for providing specific instructions on tongue configuration modifications that are needed in order to achieve /r/. This is especially important for monitoring positioning of the tongue root and sides of the tongue. Practice of /r/ should be done as a voiced segment as this seems to be more
conducive for initiation and maintenance of trilling. Vowel context and positioning of the /r/ in
the word should also be considered. Teaching /r/ in intervocalic position is more conducive for
acquisition of the segment when compared to word-initial position. It is important to take under
consideration vowel contexts as well when using intervocalic positioning as best contexts to
promote acquisition of /r/ include a low-back vowel preceding the rhotic segment (i.e. /ara/).
Limited use of contexts were the rhotic segment is preceded or followed by vowels like /u/ and /i/
should be considered as tongue root positioning for these vowels is not similar to tongue root
positioning of /r/. These differences in tongue root positioning can make it more challenging
task as the learner will be forced to change tongue root positioning during these contexts.
Additional facilitative conditions for /r/ production might surface with longer or additional of
training sessions.

This work tried to offer some potential best practices for teaching /r/ by using ultrasound
imaging and a variety of practice conditions by using a structured training protocol. The
strategies discussed in this work are of relevance to practitioners who work with populations who
exhibit difficulties with accurate production of /r/ as it can be of great importance for some
individuals to learn accurate production of /r/, especially if the individual is aware of societal
stigmas that can accompany not being able to sound more native like. Computer software used
in the clinical fields and college courses for teaching speech sounds might benefit from this
strategies in order to better facilitate acquisition of /r/ as many languages of the world share this
speech sound. As technologies become cheaper over time, imaging technologies as ultrasound
can become more readily available to more clinicians.
Appendix A. Spanish words used for initial and final assessment for accuracy of /r/ production.

<table>
<thead>
<tr>
<th>riqueza</th>
<th>rábano</th>
<th>carrucho</th>
<th>sonrisa</th>
<th>desregulaciones</th>
</tr>
</thead>
<tbody>
<tr>
<td>rubén</td>
<td>barre</td>
<td>verruga</td>
<td>monra</td>
<td>disruptiva</td>
</tr>
<tr>
<td>barro</td>
<td>agarré</td>
<td>ramón</td>
<td>sonreir</td>
<td>posrevolucionario</td>
</tr>
<tr>
<td>recibo</td>
<td>rio</td>
<td>amarra</td>
<td>enredo</td>
<td>posromántico</td>
</tr>
<tr>
<td>raciona</td>
<td>red</td>
<td>roca</td>
<td>ropaje</td>
<td>malrotar</td>
</tr>
<tr>
<td>risa</td>
<td>corri</td>
<td>rudeza</td>
<td>jarrones</td>
<td>alrededor</td>
</tr>
<tr>
<td>arrimo</td>
<td>pizarrón</td>
<td>corre</td>
<td>ropaje</td>
<td>ulrco</td>
</tr>
<tr>
<td>birrete</td>
<td>rufián</td>
<td>riachuelo</td>
<td>jarrones</td>
<td>raquel</td>
</tr>
<tr>
<td>tierra</td>
<td>corriente</td>
<td>carril</td>
<td>ropaje</td>
<td>rey</td>
</tr>
<tr>
<td>herramienta</td>
<td>ron</td>
<td>rosado</td>
<td>jarrones</td>
<td>ruleta</td>
</tr>
<tr>
<td>ruin</td>
<td>gorro</td>
<td>relajo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Appendix B. Word-Initial and Intervocalic /r/ Daily Probes lists.
<table>
<thead>
<tr>
<th>Word-Initial /r/ Daily Probes</th>
<th>Intervocalic /r/ Daily Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rusia</td>
<td>socorro</td>
</tr>
<tr>
<td>rango</td>
<td>arriba</td>
</tr>
<tr>
<td>rojizo</td>
<td>burro</td>
</tr>
<tr>
<td>reloj</td>
<td>aborreció</td>
</tr>
<tr>
<td>rafael</td>
<td>corrugado</td>
</tr>
<tr>
<td>repaso</td>
<td>erre</td>
</tr>
<tr>
<td>rutina</td>
<td>amarré</td>
</tr>
<tr>
<td>rita</td>
<td>horrible</td>
</tr>
<tr>
<td>racimo</td>
<td>burra</td>
</tr>
<tr>
<td>rosa</td>
<td>becerro</td>
</tr>
<tr>
<td>rivera</td>
<td>interrumpo</td>
</tr>
<tr>
<td>romano</td>
<td>aferrado</td>
</tr>
<tr>
<td>receta</td>
<td>narraba</td>
</tr>
<tr>
<td>rifaba</td>
<td>gorrión</td>
</tr>
<tr>
<td>rugoso</td>
<td>narren</td>
</tr>
</tbody>
</table>
Chapter IV

Spanish trill: An acoustic profile of the third formant

This research intended to better understand the acoustic profile of the apicoalveolar trill /r/ in native speakers of Spanish. There is limited data that described if /r/ and the English approximant /ɹ/ share the same acoustic characteristic of having a third formant (F3) that approximates the second formant (F2). Currently, the limited information available regarding this similarity is contradictory. It is of utmost importance to understand this the acoustic profile of /r/ as this information is used to better understand the impact of misarticulations on listeners when the acoustic signal of a sound does not match the appropriate profile of the intended speech sound. This is especially important for health services and teaching modalities that rely on using the acoustic signal of speech sounds.

To create the speech sounds of a language, individuals shape the acoustic energy produced by the vocal folds and other sources. This shaping is achieved by modifying the shape of the vocal tract using the active articulators; that is, the lips, jaw, tongue, and velum. By positioning and configuring these articulators, the vocal tract is divided into different resonating cavities. As the acoustic energy passes through these resonating cavities, it is modified or "filtered" resulting in the acoustic profile of the intended speech sound (Kent, 1997).

The speech sound class of rhotics consists of types of approximants that phonologically behave similar across many languages. However, the members of this sound class vary greatly on how they are articulated; that is, there is great variability on how the vocal tract is shaped for creating resonating cavities (Ladefoged and Madiesson, 1996). Articulatory differences across these types include but are not limited to apicoalveolar trills /r/, uvular trills /ʁ/, approximants /ɹ/, and taps /ɾ/. These differences create different acoustic profiles between each member of the rhotic class.
Furthermore, even articulatory differences for the same rhotic segment have been found across individuals that speak the same language (Tiede, Boyce, Holland, & Choe, 2004; Zhou, Espy-Wilson, Boyce, Tiede, Holland, & Choe, 2008; Rivera-Campos & Boyce, 2013). For example, the approximant /ɹ/ exhibit a variety of tongue configurations that follow a continuum from bunched to retroflex (Tiede et al., 2004) and the apicoalveolar trill /r/ can be produced by vibrating the tongue tip or vibrating one lateral side of the tongue (Rivera-Campos & Boyce 2013). In an effort to find a common characteristic across rhotics that goes beyond their similar phonological behavior across languages, researchers have turned their efforts to look for a possible trait that can better relate them. For example, the existence of an acoustical trait that is shared among all the acoustics profiles of rhotics. However, a common acoustic trait across rhotics has yet to be described.

**English Approximant’s Acoustic Profile**

The English approximant’s acoustic profile has received considerable attention by researchers when compared to other rhotics. Articulatorily, native speakers of English use a variety of tongue configurations to produce /ɹ/ using a continuum of bunched and retroflex (Tiede et al., 2004). Naturally, these different tongue configurations shape the vocal tract differently, creating diverse acoustic profiles for /ɹ/. However, all these different acoustic profiles from the various bunched and retroflex tongue configurations share a trait across all their profiles, a low F3. A F3 that approximates the F2 has been described as a consistent trait in the acoustic profile of /ɹ/ (Zhou, et al., 2008). These differences in the acoustic profiles of these various tongue configurations lays on the distance between F3 and the fourth formant (F4) with a retroflex tongue configuration for the English approximant has a F4 that moves “upwards”,
approximating the fifth formant (F5), while a bunched tongue configuration has a F4 that remains stable (Espy-Wilson, Boyce, Jackson, Narayanan & Alwan, 2000)

To successfully achieve lowering of F3 towards F2 for an adequate production of /?/, a series of constrictions that shape the vocal tract with a particular size of the frontal resonating cavity is needed. Acoustic modeling on /ʌ/ by Espy-Wilson and colleagues (2000) suggested that F3 acoustic energy is related to the size of the frontal resonating cavity including the sublingual space below tongue tip. That is, the resonating cavity anterior to the palatal constriction needs to have a certain size. Additionally, a retracted tongue root creating a constriction at the level of the pharynx appears to also have a role in aiding F3 lowering. Hamilton, Boyce, Rivera-Campos, McNeill, and Schmidlin (2013), in an ultrasound imaging pilot study, described the acoustic F3 profile of /ɹ/ productions errors by children with articulatory difficulties. A F3 that approximates F2 was observed in the acoustic profile of /ʌ/ when the individual had a retracted tongue root positioning. In contrast, a lack of a retracted tongue root positioning during /ʌ/ resulted in a stable F3 with no approximation to F2.

The complexity of a F3 approximating F2 goes even further than just frontal cavity size and a retracted tongue root. The approximation of F3 towards F2 must follow a specific parameter. After analysis of /ʌ/ productions by men and women, Hagiwara (1995) described that /ʌ/’s F3 value for an individual roughly corresponds to 60%-70% of the same individual’s F3 value for /a/ A second potential parameter has been described by Hamilton, Boyce, McCallister, and Silbert (in preparation) where the value of a perceptually correct /ʌ/ of an individual corresponds to 80% of the sum of the F3 values of the English corner vowel productions of the same individual.
Apicoalveolar Trill's Acoustic Profile

**Place of articulation.** Articulation of /r/ is done by the creation of a primary constrict and a secondary constriction. The main constriction is characterized by the multiple brief and fast apicoalveolar constrictions at the alveolar region (Ladefoged and Maddieson, 1996) while the secondary constriction is characterized by the presence of a retracted tongue root positioning (Boyce, Hamilton & Rivera-Campos, 2016). Unlike the rhotic approximant /ɹ/ that can demonstrate great variability on where the palatal constriction is made along the vocal tract (Tiede et al., 2004), the apicoalveolar trill has a more restrictive place of articulation (Recasens & Pallarès, 1999). This restrictive place appears to govern where along the alveolar region /r/ is made—posterior region of the alveols (Recasens & Pallarès, 1999). In her study, Solé (2002) observed that lingual gestures for /r/ overrides lingual gestures for vowels that are contiguous to the rhotic segment. For example, the lingual gestures of /r/ made tongue configuration for the contiguous /i/ vowel segment have a more displaced place. Solé (2002) also noted this for other vowels but /i/ showed to be the vowel segment with most displacement. On the other hand, vowels have very limited coarticulatory effects in place of articulation for /r/ (Solé, 2002). The relative precise area where /r/ has to be produced suggests that accurate production of this rhotic segment can be a challenging task.

**Aerodynamics of apicoalveolar trills.** In addition to the restrictive place of articulation, apicoalveolar trills are sensitive to aerodynamic variations (Ladefoged & Maddiesson, 1996; Solé, 2002) that can affect how /r/ can be produced. This sensitivity paired with any sociolinguistic variables of a Spanish dialect can create multiple variations on how /r/ is produced during running speech (Blecua, 2001; Henriksen & Willis 2010; Lastra & Martin Butragueno, 2006; Diaz-Campos, 2008). Canonically, /r/ is made by interrupting the air flow
with multiple brief apicoalveolar constrictions, the trilling, which is typically identified on spectographic displays by the light and dark areas which belong to the closing and opening phases respectively. The light areas (closing phases) are made by weak or absent formant energy while the dark areas (opening phases) have concentrations of energy similar to vowel formants. This trilling aspect of /r/ has made most of the acoustic research focus on describing the trilling component (number of opening and closing phases) of the segment or allophonic varieties of /r/ in languages. That is, whether /r/ is produced by just one component, two components, three or more components or if the acoustic signal reveals the existence of r-coloring voicing, sibilation or frication. Acoustic research on /r/ components offer conflicting evidence in the duration of each component as some data seem to reveal similar duration across each component (Ladefoged and Maddieson, 1996) while other data seem to have found significant differences in duration for each component (Blecua, 2001). Acoustic analysis on trill components duration by two native speakers of Spanish from Spain suggests that closing phases have a significant shorter duration when compared to the longer time duration of opening phases (Blecua, 2001). The author also notes that the more components make up a trill—the more opening and closing phases a trill possesses—a gradual but continuous descend in duration of each component is observed albeit maintaining the aforementioned observation of closing phases having a shorter duration than opening phases. Duration of trill in Spanish appears to not be influenced by any vowel contexts or its positions inside a stressed or unstressed syllable (Blecua, 2001). However, these differences can be explained by characteristics of an individual’s speech style and speed (Blecua, 2001).

Formant analysis on /r/ composed of three and five components was described by Blecua (2001). A /r/ with three components was defined by the author as having an approximant phase,
followed by an opening phase, and followed by another approximant phase. A /r/ with five components will have an approximant phase, opening phase, approximant phase, a final opening phase and one last approximant phase. The approximant phase is where there was an apicoalveolar narrowing of the vocal tract and not necessarily a total occlusion as tongue tip-palate contact does not always occur during trilling in /r/ (Whalen, Iskarous, Grathwohl & Proctor, 2010). As general observations of /r/’s acoustic profile by Blecua (2001), F1 measurements showed the biggest changes throughout the components, with higher F1 values present during the opening phases when compared to the approximant phases. On the other hand, it was reported that values of F2 and F3 were consistent across all phases. Conflicting information about this consistency of F2 across phases has been reported on a more recent acoustic analysis, as F2 has been reported to have changes in /ir/ and /ara/ contexts (Dhananjaya, Yegnanarayana, & Bhaskararao, 2012). Formant values of the edges of the /r/ segment can be influenced by contiguous vowels. This vowel influence is limited only to the opening and approximant phases closest to the vowel and not to opposite phases (Blecua, 2001). These influences at the edges of the length of the /r/ segment might be explained by the very limited coarticulatory effects that vowels exert on /r/ as previously mentioned in work by Solé (2002).

Third formant profile of /r/. Lindau (1985), described a downward movement—or approximation—of F3 towards F2 for the /r/ by a speaker of Chicano Spanish. The author suggests that a lowered F3 is a characteristic of the approximant /u/ and the apicoalveolar trill /r/. However, lowering of the F3 has not been discussed by other researchers working with more classic varieties of Spanish (Blecua, 2001; Recasens, 1991). It is important to take under consideration that these descriptions regarding the acoustic profiles of apicoalveolar trills were done with few participants and generalizations might not be plausible. These discrepancies in
the research literature and the limited amount of studies with a bigger sample of participants makes it unclear whether Spanish apicoalveolar trill is characterized by a low third formant. Furthermore, it is unclear if lowering of the third formant follows the tendency of the English approximant by lowering below the 70% of an individual’s neutral vowel.

To address some of the gaps in the literature about the acoustic F3 profile on Spanish trill, the following research work intended to answer the following research question: Does the apicoalveolar trill /r/ shows a consistent pattern across speakers as the English approximant as having a lowered F3?

**Methods**

To assess if the acoustic F3 profile of Spanish trill has a value below 70% of the third formant of a neutral vowel, acoustic measurements of /r/ in different word positions and different vowel contexts were analyzed. Nineteen adult native speakers of different Spanish dialects were recruited. Each participant read aloud a series of Spanish words containing initial and intervocalic trill in different vowel contexts. The Spanish dialects represented in our data come from countries in North, Central, and South America as well as Europe and Caribbean. Table 1 provides information of Spanish dialects represented in our data. Due to the great variation of Spanish dialects among countries, differences in trill production can occur among users of Spanish (Blecua, 2001; Henriksen & Willis 2010; Lastra & Martin Butraguño, 2006; Diaz-Campos, 2008). Some speakers of Spanish differentiate between dialectal forms of Spanish that are considered more prestigious or educated than others (Zentella, 1997). To control for biasing the participants towards the use of one type of dialect over another, participants were not instructed on how to read the words presented to them.
Table 1. Spanish dialects and number of native speakers represented in our data

<table>
<thead>
<tr>
<th>Spanish Dialect</th>
<th>Number of Speakers</th>
<th>Spanish Dialect</th>
<th>Number of Speakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chile</td>
<td>1</td>
<td>Cuba</td>
<td>1</td>
</tr>
<tr>
<td>Colombia</td>
<td>7</td>
<td>Spain</td>
<td>1</td>
</tr>
<tr>
<td>Mexico</td>
<td>3</td>
<td>Argentina</td>
<td>1</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>4</td>
<td>Venezuela</td>
<td>1</td>
</tr>
</tbody>
</table>

To assess if the acoustic profile of Spanish apicoalveolar trill has F3 profile that falls below 70% of a Spanish neutral vowel, similar to the acoustic F3 profile of the English approximant, the acoustic software Wavesurfer was used to measure formant values of /r/. Spectographic displays of the words read by each participant were visually inspected for localization of /r/ by looking for the multiple interruptions on the formant band. To corroborate localization of /r/, listening to the audio segment followed the visual inspection to ensure /r/ sound was accurately identified. Because only classic or canonical productions of /r/ were analyzed, measurements of F2 and F3 were made on trills that had a minimum of three components; a closing phase followed by an opening phase followed by another closing phase. Measurements of F2 and F3 were made at the opening phase closest to the region that delimits half of the duration of the entire /r/ segment.

In order to assess if lowering of the third formant for /r/ lowers as much as for English approximant /ɹ/, as described by Lindau (1985), the observation from Hagiwara (1995) will be assessed on /r/. To do this, the following procedure was replicated across each participant. F3 formant measurements of trills at word initial position were obtained. These values were then grouped together by vowel contexts: front and back vowel contexts. F3 values of word initial
trills followed by front vowel contexts (i.e. /i/, /e/) were summed and averaged. Same was done 
with word initial trills followed by mid-back vowel contexts (i.e. /a/, /o/, and /u/). Intervocalic 
trill contexts were not subdivided by low or mid-back vowel contexts as there are limited words 
that follow this criteria. The values that correspond to 70% of the averaged F3 formant value for 
/a/ were then obtained. Finally, to compare if the acoustic F3 profile of Spanish trill follows the 
same pattern as the English rhotic /ɹ/ the averaged F3 values of each previously grouped trill 
were compared to the values that correspond to 70% percent of the individuals averaged F3 
value of /a/. An averaged F3 value of word initial or intervocalic trill was considered to follow 
the profile of the English approximant if the averaged value obtained falls below the value 
corresponding to 70% of the averaged F3 value of the individual’s /a/.

Results

Univariate analysis of variance (ANOVAs) demonstrated no statistically significant 
differences between word-initial /r/ with mid-back vowel context, word initial /r/ with front 
vowel context, and intervocalic /r/; F (2,54) = 1.00, p=.375. Only Participant 2 showed a low F3 
for /r/ when the rhotic segment was followed by a back vowel. Table 1 shows a binomial scoring 
system for /r/’s F3 acoustic profile. Rhotics contexts that showed a lowered F3 similar to the 
English approximant scored a 1 while /r/ otherwise a score of 0 was given.
Table 1. Apicoalveolar /r/’s acoustic profiles were F3 showed a similar profile as the English approximant.

<table>
<thead>
<tr>
<th>Participant</th>
<th>F3 Rv Back</th>
<th>F3 Rv Front</th>
<th>F3 vRv</th>
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</thead>
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<tr>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1</strong></td>
<td><strong>0</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

Discussion

Our data suggests that /r/ in Spanish does not follow the acoustic pattern of American English /ɹ/ as it does not consistently show a lowered F3. To better understand why a F3 may not be an acoustical trademark for /r/ as it is for /ɹ/ we might need to take under consideration how both rhotics are produced. As previously discussed, approximation of F3 towards F3 in the acoustic profile of /ɹ/ is achieved by a combination of context. Briefly, lowering of F3 in /ɹ/ is aided by the presence of a retracted tongue root positioning (Hamilton, 2013) and the size of the frontal resonating cavity including the sublingual space (Espy-Wilson et al., 2000).
Tongue configuration for the apicoalveolar trill /ɾ/ shows some common articulatory characteristics with retroflex tongue configuration for /ʂ/. These similarities are the presence of a sublingual space as well as having a retracted tongue root positioning. However, as seen in our data, patterning of a low F3 across speakers was not observed for /ɾ/ productions on all the vowel contexts and positioning studied in this work. The absence of this patterning, even though tongue configuration for /ɾ/ and retroflex tongue configuration for /ʂ/ have some similarities, the restrictive place of articulation for /ɾ/ could explain our observations for /ɾ/’s F3 profile.

As /ɾ/ exhibits a very restrictive place of articulation, observed by the limited area along the alveolar region (Recacens & Pallarès, 1999) and the limited coarticulatory effects adjacent vowels exert on the /ɾ/ segment (Solé, 2002), the dimensions of the frontal resonating cavity could not be enough to aid in lowering of F3 in the same way it aids for the English approximant. Visual inspection of MRI pictures from Tiede et al., (2004) show that retroflex tongue configurations of /ʂ/ have the primary constriction at a more palatal place compared to an alveolar place. In the case of /ɾ/, the information gathered by Recacens and Pallarès (1999) show that contacts between the frontal parts of the tongue and the palate are located at the posterior regions of the alveolar region.

If /ɾ/ is made at the alveolar region, a more anterior place when compared to retroflex tongue configuration for /ɾ/, the dimensions of the frontal resonating cavity—for the same individual producing /ʂ/ and /ɾ/—will possess less dimension during /ɾ/ production. Thus, lowering of F3 to match /ʂ/’s F3 might not be plausible. Lindau’s (1980) observation of a trill produced by a speaker of Chicano Spanish with a lowered F3 could suggest that /ɾ/ production in Chicano Spanish occurs at a more posterior region of the alveolus when compared to speakers of more classical Spanish dialect. However, more information is needed to better understand the
potential presence of linguo-palatal contact differences between speakers of Chicano Spanish and other Spanish dialects.

More research is needed to better comprehend the acoustic profile of /r/. Although this research helped in expanding our current understanding of /r/’s F3 acoustic profile, it is still unclear what is the source for /r/’s F3 values. Additionally, it is unclear what if there is a lowering threshold for /r/’s F3 that is not the one studied on this research.
Chapter V

General Discussion

The Role of Phonetic Knowledge and Formal Instruction

The results from each of our research studies have provided more information to better understand various aspects of the apicoalveolar trill /r/. Specifically, its articulatory requirements, teaching strategies, and acoustic profile. Overall, the studies in this work feed from each other as there is a mutual relationship between our phonetic knowledge of /r/ and how we use that information to teach production a sound to individuals who require formal instruction. Detailed phonetic knowledge of /r/ benefits teaching approaches that rely on instructing adequate positioning of the frontal parts of the tongue as these approaches can be modified to include more comprehensive instructions that incorporate the back portions of the tongue. Additionally, phonetic knowledge allows to further our understanding of the acoustic profile of the rhotic segment which is important for teaching models that rely on using the acoustic signal of the sound.

Tongue Root Configuration of /r/ and its Role in Formal Instruction

To expand the phonetic literature on /r/ production, our imaging results show that a tongue configuration for /r/ is characterized by a retracted tongue root positioning. As part of the articulatory requirements of /r/, this is relatively new information and it is seldom suggested in the phonetic literature. This new information impacts how future instruction on /r/ production should be approached. Although the commonly used phonetic descriptions of /r/ have aided some individuals to attain acquisition, some continue to fail. For these subset of individuals, a more comprehensive phonetic teaching that trains positioning of the back and anterior portions of the tongue could provide more useful for learning /r/.
Strategies for Teaching /r/ in Formal Instruction

As our current practices for teaching trill mirror our current knowledge of how the sound is articulated, formal instructions that go further than just instructing how to perform apical trilling are limited. To advance our pedagogical field in teaching /r/, our second study aimed at incorporating the use of imaging technology and various potential teaching contexts—including our new knowledge of tongue root positioning for instructing /r/ production. Our second study was innovative in two ways as it (1) used ultrasound imaging technology for teaching tongue configuration for /r/ and (2) explored various teaching techniques with potential to promote /r/ acquisition. We found that ultrasound imaging technology was helpful for teaching, monitoring, and provide feedback regarding positioning of the various parts of the tongue when attempting to produce /r/ (i.e. elevation of the lateral sides of the tongue). Conventional approaches do not allow for such level of information and it can be challenging to know with precision what portions of the tongue have been inadequately positioned when a distorted /r/ was produced. To complement the use of ultrasound, various strategies to promote /r/ production were explored. Learners of /r/ seemed to benefit the most from the following learning contexts: (a) production of /r/ at intervocalic position, (b) production of the /r/ as a voiced segment, (c) production of /r/ where the rhotic segment is either preceded or followed by vowels that require a retracted tongue root positioning and (d) a retracted tongue root positioning. Detailed rationales for the effectiveness of these strategies are not clear. However, some of these appear to facilitate and maintain positioning of the tongue root at the back portion of the oral cavity (i.e. combined used of use of certain vowel contexts and positioning of /r/ in intervocalic positioning), which we have already discussed as a requirement for /r/ production.
Acoustic Profile and its Role in Formal Instruction

Our last research explored the acoustic signal of /r/ as the research literature describe different acoustic profile for the third formant of the rhotic. Some data have suggested that /r/’s F3 approximates F2—just like what has been observed for the English approximant—while different data does not report such observation. Our results suggests that /r/’s F3 profile does not follow the same pattern as the English approximant. This has created more questions that should be addressed in future research. For example, identifying /r/’s source for F3 and analyzing if native speakers use a specific formant profile from the acoustic signal for /r/ to identify accurate production of the sound. More research is needed for better understanding /r/’s acoustic profile as this will be beneficial for understanding the impact of misarticulations on the listener, teaching practices that use the acoustic signal of /r/ to identify accurate production of the sound as well as for long distance service delivery models such as telehealth.

Overall Conclusions

We have gathered data that should be taken under consideration for expanding the phonetic, clinical and pedagogical literatures on /r/. As /r/ is shared among many languages of the world, misarticulations of this sound impacts speech intelligibility and in some cases, societal status.
References


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