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Speech characteristics of monozygotic twins and a same-sex sibling: an acoustic case study of coarticulation patterns in read speech

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Running head: Coarticulation patterns in monozygotic twins

ABSTRACT

This case study reports on an acoustic investigation of the motor speech characteristics of a set of young adult male monozygotic (MZ) twins and compares them to those of an age- and sex-matched sibling who participated in the study two years later to match for demographic factors. Coarticulation patterns were investigated from read samples of Consonant-Vowel (CV) sequences in monosyllabic words containing a variety of consonants and vowels. This was done by examining F2 vowel onsets and F2 vowel targets, plotted as F2 locus equations. Data were processed for between sibling differences using a number of statistical tests. Results indicated that the MZ twins displayed F2 parameters, and coarticulation patterns which were more similar than those of their age- and sex-matched sibling. The results of this case study therefore suggest that acoustic phonetic parameters used to index coarticulation patterns have the potential to profile some of the similarities and differences in the speech characteristics of genetically related individuals.

Keywords: Monozygotic twins; human; coarticulation patterns; development; motor speech skills; genetic; acoustic phonetic

INTRODUCTION

The influence of genetics and heredity on language development and developmental language disorders has been widely investigated using family studies (Flipsen, Shriberg, Weismer, Karlsson & McSweeney, 2001; Lewis & Freebairn, 1997; Spitz, Tallal, Flax & Benasich, 1997; for a review see Stromswold, 1998; Shriberg, Flipsen, Karlsson & McSweeney, 2001), and twin studies (Hay, Prior, Collet & Williams, 1987; Hohnen & Stevenson, 1999; Lewis & Thompson, 1991, 1992; Locke & Mather, 1989; Matheny & Bruggemann, 1972, 1973; Mather & Black, 1984; Mittler, 1976; Munsinger & Douglas, 1976). There is evidence to suggest that monozygotic (MZ) twins have high levels of concordance for speech and language development (Lenneberg, 1969; Locke & Mather, 1989; Matheny & Bruggemann, 1973), and speech and language disorders (Lenneberg, 1967, 1969; Lewis & Thompson, 1991, 1992). A theme that emerges from these studies is that in normal development, MZ twins display a tendency to share both articulation and misarticulation patterns (Locke & Mather, 1989; Matheny & Bruggemann, 1973). In addition, articulation disorders account for most of the types of speech and language disorders reported for MZ twins (Lewis & Thompson, 1991, 1992). This, and the concordance of verbal ability in MZ twins (Plomin, DeFries & McClearn, 1990; Plomin, DeFries, McClearn & Rutter, 1997), corroborates earlier accounts of genetic influences on speech and language development (Lenneberg, 1967, 1969). Furthermore, the verbal ability of MZ twins appears to be related to other areas of their language performance. For example, in a twin study of children aged 6 to 12 years, which investigated specific cognitive abilities (verbal, spatial, speed and memory) and scholastic achievement (reading, maths and language), there was evidence to suggest "substantial overlap in the genes that affect verbal ability and reading achievement." (Thompson, Detterman & Plomin, 1991, p. 161).

Both morphological (Locke & Mather, 1989), cognitive and neuromuscular factors (Matheny & Bruggemann, 1973) have been proposed as explanations for the greater overlap in the articulation skills of MZ twins when compared to dizygotic (DZ) twins. These suggestions are supported by recent evidence which suggests that those brain structures which subserve speech and language input and output processing (e.g., sensorimotor cortex, linguistic cortices such as Broca's and Wernicke's areas as well as frontal brain regions) are also influenced genetically , and that MZ twins display very high levels of similarity in these brain regions (Thompson, Cannon, Narr, van Erp, Poutanen, Huttunen, Lönnqvist, Standertskjöld-Nordenstam, Kaprio, Khaledy, Dail, Zoumalan & Toga, 2001; Plomin and Kosslyn, 2001).

Studies investigating the acoustic characteristics of twins' speech

Despite the overwhelming evidence for the high levels of concordance in the normal development of verbal ability and articulation skills of MZ twins, relatively few studies have investigated the speech or voice characteristics of MZ twins using acoustic analysis (Forrai & Gordos, 1983; Fuchs, Oeken, Hotopp, Täschner, Hentschel & Behrendt, 2000; Nolan & Oh, 1996; Przybyla, Horii & Crawford, 1992). Using read speech (The Rainbow Passage - Fairbanks, 1960), and a large twin sample, Przybyla and colleagues found that MZ twins displayed higher levels of similarity than DZ twins in vocal fundamental frequency (VFF), therefore suggesting that VFF was influenced by genetic factors (Przybyla, Horii & Crawford, 1992). Similar findings have also been reported more recently (Fuchs, Oeken, Hotopp, Täschner, Hentschel & Behrendt, 2000). However, an earlier study found that intra-pair differences in vocal fundamental frequency alone were not sufficient in determining the zygosity of same-sex twin pairs. Instead, it was found that when 14 acoustic parameters were combined (e.g. fundamental frequency, standard deviation of fundamental frequency, vowel formant frequency parameters), perfect determination of zygosity was achieved for a sub-group of twin pairs (Forrai and Gordos, 1983). In addition, although there is some acoustic evidence that some MZ twins display similar coarticulation patterns, other data suggests that some pairs of MZ twins display differences in their speech patterns. For example, Nolan and Oh (1996) found some inter-twin disparities in the acoustic patterns and phonetic realisations of the alveolar approximant /r/, and the lateral approximant /l/. Nolan and Oh (1996) also report however, that different twin sets displayed greater or fewer inter-twin similarities. This therefore suggests that the degree of similarities in twins' speech is not uniform across twin pairs.

By examining the speech patterns of MZ twins using acoustic analysis, it is possible to gauge their motor speech skills indirectly, and assess the level of similarity in these fine motor skills. By adopting such an approach it is therefore possible to examine the spectral characteristics of their speech, and assess the degree of resemblance in these acoustic structures within MZ twin pairs. If the speech patterns of MZ twins are highly similar, this could be the result of not only their shared physical (e.g. vocal tract morphology) characteristics, but also their shared genes, and shared environments (see Plomin & Kosslyn, 2001). In fact, in order to investigate the speech patterns of MZ twins, it is necessary to ensure that they share the same language and the same speech community environment because of differences that exist across different languages, dialects, and accents, and the influence of these factors on speech and language. By examining the extent of the similarities and differences in speech parameters within MZ twins, and comparing these with DZ twins or siblings, it may be possible to assess the extent of genetically-shared and environmental influences on motor speech characteristics.

Investigation of speech characteristics from coarticulation patterns using F2 locus equations

What is coarticulation? In the pronunciation of the word 'do' ([du]), for example, a speaker will begin to round their lips in anticipation of the rounded vowel [u] before the release of the lingual closure for [d]. This overlap in articulatory gestures for the consonant and vowel, both temporally and spatially, is known as coarticulation. The acoustic consequences of this gestural overlap can be observed in the systematic variations of formant frequency values at the boundary of [d] and [u]. In particular, the second formant frequency at the boundary of [d] displays systematic covariation (correlation) with the vowel target, therefore reflecting anticipatory articulation. These systematic correlations can be captured using F2 locus equations, which parameterise the relationship between F2 mid and F2 onset values of vowels in consonant-vowel sequences (Lindblom, 1963; Duez, 1992; Krull, 1989; Nearey & Shammass, 1987; Sussman, McCaffrey & Matthews, 1991; Sussman, Hoemeke & McCaffrey, 1992; Sussman, Dalston & Gumbert, 1998; Sussman, Fruchter, Hilbert & Sirosh, 1998), and provide an indirect representation of the dynamics of lingual gestures which are involved in the production of consonant-vowel sequences.

Locus equations are phonetic descriptors of place of articulation (Sussman, McCaffrey & Matthews, 1991; Sussman, Hoemeke & McCaffrey, 1992; Sussman, Dalston & Gumbert, 1998; Sussman, Fruchter, Hilbert & Sirosh, 1998) which depict the linear relationship between the F2 mid vowel (or target) frequencies (plotted along the x-axis) and F2 vowel onset frequencies (plotted along the y-axis) of consonant-vowel (CV) sequences in CVC syllables. Locus equations are expressed by simple regression functions as F2vowel onset = k * F2mid vowel + c, where k represents the slope of the function and c, the y-intercept. It has been established that the slopes of these regression lines vary with the place of articulation (Sussman, McCaffrey & Matthews, 1991; Sussman, Hoemeke & McCaffrey, 1992; Sussman, Fruchter & Cable, 1995; Sussman, Dalston & Gumbert, 1998; Sussman, Fruchter, Hilbert & Sirosh, 1998; Tabain & Butcher, 1999; Tabain, 2000; Sussman, 2002) and that the steepness of these slopes is indicative of the extent to which consonant and vowels coarticulate. Steeper slopes occur where there are high levels of covariation between the F2 onset and F2 target values of a vowel in a CV syllable as is often the case for bilabial plosives for example, and therefore provide an index of higher degrees of coarticulation (Sussman, McCaffrey & Matthews, 1991; Sussman, Hoemeke & McCaffrey, 1992; Sussman, Dalston & Gumbert, 1998; Sussman, Fruchter, Hilbert & Sirosh, 1998; Sussman, 2002). On the other hand, shallower slopes which tend to occur for alveolar consonants (Sussman & Shore, 1996) would be indicative of low levels of covariation, and therefore, less coarticulation between the F2 onset and F2 target values of a vowel in a CV sequence of a CVC syllable. Examples of scattergraphs depicting F2 locus equations are provided in Figure 3.

The input processing (i.e. perceptual) relevance of the relationship between vowel onsets and vowel targets of F2 as expressed by F2 locus equations has both its proponents and its critics (see Sussman, Fruchter, Hilbert & Sirosh, 1998 for a review and commentaries). However, there is some evidence to suggest that the acoustic phonetic data which they represent (i.e. vowel onset and mid vowel F2 values) play some role in perception. For example, their perceptual role has been demonstrated using synthetic stimuli (Fruchter & Sussman, 1997). Further evidence is provided where it is shown that speakers display very similar F2 locus equation functions for speech produced both with and without bite-blocks (Sussman, Fruchter & Cable, 1995). The highly similar F2 locus equation functions for these two conditions suggest that in the bite-block condition, compensatory articulatory gestures are operating to maintain the acoustic relationship (and therefore auditory perceptual cues for consonants which include F2 parameters), between the onset and target values of the vowels in CV(C) syllables (Sussman, Fruchter & Cable, 1995). The evidence that F2 locus equations display emerging developmental patterns during infancy and early childhood further highlights the importance of the perceptual relevance of the relationship between F2 onset and F2 target values expressed by F2 locus equations (Sussman, Minifie, Buder, Stoel-Gammon & Smith, 1996; Sussman, Duder, Dalston & Cacciatore, 1999).

This case study reports on a preliminary investigation of coarticulation parameters and patterns in the read speech of one set of young male adult MZ twins, and an age- and sex-matched sibling. Earlier studies have reported some evidence of both perceptual and acoustic similarities in the speech of the MZ twins investigated here (Whiteside and Rixon, 2000, 2001). The aim of this case study was to investigate the speech patterns of the twins further, and compare them with those of their sibling by examining their coarticulation patterns in CV sequences within a set of CVC monosyllabic words in a variety of phonetic contexts. This was done by measuring formant frequency onset and mid vowel (target) values for the second formant frequency, and deriving F2 locus equations as one method of characterizing coarticulation patterns. On the basis of their shared accent, dialect, environmental influences, and physical characteristics, it was predicted that although all three siblings would share some coarticulation patterns, there would be evidence of a higher degree of similarity between the coarticulation patterns displayed by the MZ twins compared to their age- and sex-matched sibling.

METHOD

Subjects

A pair of MZ twins (T1 and T2) and one of their male siblings (S) participated in the study. Details of their respective heights and weights are given in Table 1. From the physical similarities between all three siblings, and the significant positive correlation between vocal tract length and height and weight (Fitch and Giedd, 1999), it could be inferred that they all share similar vocal tract lengths. On an impressionistic level, the twins' voices were judged to be very similar in quality. Using a subset of the data to be reported here, a prior study had shown that although the twins were identified accurately by family and friends above chance, the level of accuracy averaged around 72%, therefore suggesting some degree of overlap in their speech characteristics. Furthermore, this was confirmed by the presence of similarities between their speech parameters (Whiteside and Rixon, 2000), and reconfirmed using the full data set in a later study (Whiteside and Rixon, 2001). The accent and speaking styles or idiolects were in general judged to be very similar across all 3 siblings. The twins were 21 year-old Southern Irish males with no history of speech, language or hearing problems. Their sibling S was a 20 year-old male who like the twins had no history of speech, language or hearing problems, and had resided at home (Dublin) until he left to attend the same higher education institution (a University in Sheffield) as the twins. A period of two years had elapsed between the participation of the twins and the sibling in order to match factors such as age, and environmental influences such as the ambient local accent, which is markedly different between Dublin and Sheffield (Foulkes & Docherty, 1999).

Speech material

All 3 siblings were recorded using a Sony DAT recorder (model TCDD100) and a high quality Sony microphone (model ECMMS907). They read 5 word lists in a quiet room. Each word list consisted of the same 32 words presented in different random orders so that 5 productions of each word were obtained altogether, and a potential 160 words per sibling. The words were monosyllabic, of the structure consonant-vowel-consonant (CVC), and contained a variety of vowels with initial consonants having bilabial, alveolar, velar and glottal places of articulation (/b/, /d/, /g/ and /h/). The entire list of monosyllabic words (and relevant vowel contexts) is as follows: bead ([iː]), bib ([ɪ]) , bid ([ɪ]), bed ([ɛ]), bird[1] ([əʵː]), bad ([aː]), bob ([ɒ̞ː]), bored[1] ([oʵː]), bud ([ʊ]), dab ([aː]), deed ([iː]), did ([ɪ]), dog ([ɒ̞ː]), dad ([aː]), dead ([ɛ]), daub ([ɒ̞ː]), dude ([üː]), dub ([ʊ]), dud ([ʊ]), dug ([ʊ]), gig ([ɪ]), gag ([aː]), god ([ɒ̞ː]), good ([ʊ]), heed ([iː]), hid ([ɪ]), head ([ɛ]), had ([aː]), heard[1] ([ə˞ː]), hard[1] ([ɐ˞ː]), hoard[1] ([o˞ː]), hood ([ʊ]).

Each word list had 4 'dummy' items (word tokens) at the beginning to give the speakers time to adjust to the task. There were also 5 'dummy' items at the end of the list to allow for possible increase of speaking rate or decrease in volume or lowering of pitch that may possibly have occurred towards the end of the reading task. All 3 speakers were instructed to read the words using their habitual reading voices, and a steady even pace so as to avoid any performance behaviours that might have resulted in an unusual degree of variation in pitch, volume or speed of presentation. A total of 10 words were misread by the siblings (3 by T1, 2 by T2 and 5 by S), which represented a data loss of 2.1% (10/480 * 100).

Acoustic analysis: second formant frequency parameters

A total of 470 monosyllabic words were digitised using a Kay Elemetrics Computerized Speech Laboratory (CSL, model 4300) using a sampling rate of 16 kHz. Sound pressure waveforms and wideband (183 Hz) Fast Fourier Transform (FFT) spectrograms of the monosyllables were then generated and analysed using the CSL. In order to investigate coarticulation patterns, second formant frequency (F2 - in Hz) measurements were taken at the onset (vowel onset) and temporal midpoint (mid vowel) for the vowel portion of each monosyllabic word (see Figure 1 for sampling points). It is acknowledged that vowels may be realised as monophthongs or diphthongs. Vowel targets represented at the temporal midpoint may therefore not adequately capture this variability in vowel realization, particularly across speakers from a wide range of ages, accents and backgrounds. However, all three age-matched siblings shared the same accent and idiolect. The choice of the temporal midpoint was therefore not viewed to be problematic for the aims of the current preliminary study. The formant frequency measurements were obtained from the wideband spectrograms using a hair crossed-line cursor, which provided an automatic frequency readout at the intersection point of the cursor. Formant frequency values were measured at the mid frequency point of each formant frequency band.

[1] These words indicate those CVC words that contain rhotacised ('r-coloured') vowels in this Irish accent.

Reliability of formant frequency analysis

In order to provide a measure of reliability for the analysis of formant frequency values, 20% of the CVC syllables were reanalyzed by the same experimenter (SPW) 9 months after the original analysis had been performed. Statistical comparisons between both sets of measurements of formant frequency onsets and temporal midpoints were performed using statistical methods which have been adopted elsewhere (Sussman & Shore, 1996; Sussman, Duder, Dalston & Cacciatore, 1999). Both absolute differences and Pearson's correlation coefficients were derived for the onset and temporal midpoints of F2 obtained from the original analysis and the re-analysis. The results of the reliability analysis were as follows. F2 onset: r=.994, mean absolute difference = 36.0 Hz; F2 mid: r=.995, mean absolute difference = 38.9 Hz. These reliability measures compare favourably with previously published data on F2 onset and F2 vowel measures (Sussman & Shore, 1996; Sussman, Duder, Dalston & Cacciatore, 1999).

F2 locus equations and simple regression functions

F2 locus equations were generated using a simple regression function (1) where k represents the slope of the function and c, the y-intercept.

$$\text{F2vowel onset} = k * \text{F2mid vowel} + c \qquad (1)$$

F2 locus equations were derived for the twins (T1 and T2) and sibling (S) for each place of articulation (bilabial, alveolar, velar[2], and glottal). The F2 vowel onset and F2 mid vowel values were the 'onset' and 'temporal midpoint' values described above (see section on *Acoustic analysis* above).

[2] Because of the limited numbers of samples available for front and back vowel contexts, values were combined for the velar place of articulation.

Euclidean distances separating siblings and Euclidean distances separating consonants

The y-intercept values for each of the F2 locus equations were divided by 2000 to provide a normalised set of values between 0 and 1 (Sussman, Dalston & Gumbert, 1998). Slope values were subsequently plotted against corresponding normalised y-intercept values for the F2 locus equation functions of all three siblings (twins T1 and T2, and sibling S)[3] to provide a simplified higher order locus equation acoustic space for all 4 places of articulation (Sussman & Shore, 1996; Sussman, Dalston & Gumbert, 1998). This higher order space was then used to calculate two sets of Euclidean distances to examine between sibling differences. Firstly, Euclidean distances separating each sibling for each consonant (i.e. T1 - T2 for /b/, /d/, /g/, /h/; T1 - S for /b/, /d/, /g/, /h/; T2 - S for /b/, /d/, /g/, /h/). Secondly, Euclidean distances separating the consonant categories for each sibling (/b-d/, /d-g/, /g-h/, /h-b/). Euclidean distances were calculated using formula (2).

$$\sqrt{((x_1-x_2)^2 + (y_1-y_2)^2)} \qquad (2)$$

Simple linear regression modelling of F2 vowel onset and F2 mid vowel values : the application of Chow tests to test between sibling differences

Simple linear regression functions of vowel onset and mid vowel values for F2 were tested for between sibling differences by applying a series of Chow tests for each place of articulation (bilabial, alveolar, velar and glottal). The Chow test is used to test the equality between sets of coefficients in two linear regressions (Chow, 1960; Maddala, 2001). So for example, when a

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[3] From this point onwards the term "siblings" will be used to refer to T1, T2, and S collectively. Any reference to S alone or to the twins T1 and T2 will be clarified to the reader.

simple linear regression model is used to represent the relationship between mid vowel and vowel onset formant frequency values, and therefore a measure of coarticulation, one could investigate whether the same linear relationship between mid vowel and vowel onset holds for different individuals; in this case, a set of MZ twins and an age- and sex-matched sibling. This question can be answered by testing whether two sets of observations can be pooled and modelled by the same regression model. An example would include testing for differences between the mid vowel and vowel onset formant frequency data for T1 and T2. In order to test for this, a regression function modelling the pooled data for T1 and T2 for each place of articulation would be compared with the separate regression functions for T1 and T2 for each place of articulation, which would be subsequently combined to see if there were any significant differences between the pooled data and the combined regression functions. The Chow test is based on the assumption of equal variance. Therefore, homogeneity of variance tests were carried out on all F2 mid vowel and F2 vowel onset data used in the 4 models outlined below using Levene's statistic (SPSS, 1999). Results indicated equality of variance for all the data used in the 4 models for all places of articulation (see Table 2), and therefore supported the use of the Chow tests.

The 4 models of the Chow test which were applied to test for between sibling differences in the regression functions of formant frequency mid vowel and vowel onset values for F2 for each place of articulation were as follows.

Model 1 tested for differences between T1 and T2 by comparing the regression functions of the pooled data for T1 and T2 compared to the combined separate regression functions for T1 and T2. If no significant differences were found between the pooled data of T1 and T2 and the combined separate regression functions of T1 and T2, this would suggest that the two sets of observations can be pooled for T1 and T2 and modelled by the same regression function.

Model 2 tested for differences between the pooled data of the T1, T2 and S compared to two separate models for both T1 and T2 (pooled), and S. If no significant differences were found between the pooled data of T1, T2 and S and the combined separate regression functions of T1 and T2 (pooled), and S, this would suggest that the both sets of observations can be pooled for T1 and T2 and S can be modelled by the same regression function.

Model 3 tested for differences between T1 and S by pooling the data for T1 and S compared to the regression functions of T1 and S modelled separately. If no significant differences were found between the pooled data of T1 and S and the combined separate regression functions of T1 and S, this would suggest that the both sets of observations can be pooled for T1 and S can be modelled by the same regression function.

Model 4 tested for differences between T2 and S by pooling data for T2 and S compared to the values for T2 and S modelled as two separate regression functions. If no significant differences were found between the pooled data of T2 and S and the combined separate regression functions of T2 and S, this would suggest that the both sets of observations can be pooled for T2 and S can be modelled by the same regression function.

RESULTS

F2 vowel onset and F2 mid vowel formant frequency values

Table 3 provides the mean and standard deviation values for the F2 vowel onset and F2 vowel target (mid) data for T1, T2 and S by word token, and by the initial consonant's place of articulation. On a token by token basis, the F2 onset and F2 vowel target values in Table 3 reflect a number of phonetic context effects and individual differences which deserve some attention. We will first turn our attention to the some key phonetic context effects in the data.

The F2 onset and F2 target values show evidence of being contextually conditioned by the vowels in the CVC syllables. For example, in the case of the bilabial place of articulation, the values for the front vowel contexts (e.g. [i] in 'bead', [ɪ] in 'bib', 'bid') are higher than those for the more centralised (e.g. [ɛ] in bed, [ə˔ː] in 'bird'), and back vowels (e.g. [ɒ̜ː] in 'bob', [o˔ː] in 'bored'). The nature of this vowel context conditioning is also evident for the glottal place of articulation, where similar vowel context effects on both the F2 onset and F2 target data are observed. For example, the front vowel contexts (e.g. [i] in 'heed', [ɪ] in 'hid') display higher values than the more centralised (e.g. [ə˔ː] in 'heard') and back vowel (e.g. [ʊ] in 'hood', [o˔ː] in 'hoard') contexts. Although the F2 onset and F2 target values for the alveolar and velar places of articulation also display vowel context effects, vowel onset values appear to display more variation according to both the initial consonant and the vowel context. For example, in the case of the alveolar tokens, the F2 onset values for the front vowel contexts (e.g. [i] in 'deed', [ɪ] in 'did') are closer in value to the F2 target values compared to the back vowels (e.g. [ɒ̜ː] in 'daub', 'dog'; [ʊ] in 'dub', 'dud', 'dug') which display F2 onset values which are appreciably higher. These F2 patterns reflect the allophonic variations which arise from the articulatory constraints and kinematics involved in the production of /dVC/ syllables. The small differences between the F2 onset and F2 target values for the front vowel contexts reflect the smaller lingual movements from the anterior alveolar plosive to the close anterior palatal constrictions which are typical for front vowels. This contrasts with the larger differences between the F2 onset and F2 target values observed for the back vowels, which reflect larger lingual movements from the anterior alveolar plosive to the posterior velar/pharyngeal constrictions, which are typical for these vowels. Allophonic variations can also be seen in the data for the velar place of articulation. Here, smaller F2 onset/F2 target differences are observed for the close front vowel context ([ɪ] in 'gig') compared to the more open vowel contexts (e.g. [aː] in 'gag', [ɒː] in 'god'). Again, these allophonic variations can be explained in terms of the articulatory constraints and kinematics involved in the utterances of presented in this study; larger differences will reflect more extensive articulatory transitions/movements.

If we turn now to individual differences, we are able observe the following key trends by place of articulation. Firstly, for the bilabial data set T1 and T2 display similar F2 onset to F2 target changes for the word tokens 'bad', 'bed' and 'bob'. In addition, the token 'bud' displays greater similarities between T1 and S, and the tokens 'bead' and 'bird' display greater similarities between T2 and S. Secondly, for the alveolar data set T1 and T2 display comparable F2 onset to F2 target changes for 'dud'. In addition, 'dad' and 'dog' display greater similarities between T1 and S, whereas the F2 changes are more similar between T2 and S for the word token 'dead'. Thirdly, the velar data display the following individual differences. T1 and S display more similar F2 changes for 'gig' and 'gag', whereas the word tokens 'gag' and 'god' display greater similarities in F2 changes between T1 and S, and T2 and S, respectively. Finally, in the case of the glottal data set, the word tokens 'hard', 'heard' and 'hood' displayed F2 changes which were the most similar for T2 and S. This contrasted with only one token ('head') which displayed the greatest similarities between T1 and T2.

The mean values (+/- 1 SE of the mean) for the F2 vowel onset and F2 vowel target data across all tokens are provided in Figure 2 for each sibling (T1, T2 and S) by place of articulation. Turning first to phonetic context effects, the bilabial (see Figure 2(a)) and glottal (see Figure 2 (d)) places of articulation displayed rises in F2 values from the onset to the target values, thereby reflecting rising F2 transitions for these two places of articulation. The rising F2 transition patterns across all tokens are typical for the bilabial place of articulation. The alveolar (see Figure 2 (b)) and velar (see Figure 2 (c)) places of articulation displayed falls in F2 values from the onset to target values, thus reflecting falling F2 transition patterns. In the case of the alveolar place of articulation, this falling F2 transition pattern is typical for all vowel contexts except close front vowels (e.g. /iː/), and in some cases mid vowels (e.g. /ɛ/), which display rising and flat transitions, respectively. The first of these phonetic context effects is reflected in the F2 onset and F2 mid values for the close front vowel /iː/ (in 'deed') for all three siblings (see Table 3). If we now turn to individual differences, we are able to note from Figure 2 that T1 and T2 displayed higher F2 onset and F2 target values compared to S, and this was the case for all places of articulation.

Table 4 provides the results of a General Linear Model repeated measures test (by sibling) for F2 vowel onset and F2 mid (target) vowel data. The results of between sibling comparisons with Bonferroni adjustment for multiple comparisons are also given in Table 4. There were significant sibling effects for both formant frequency parameters (see Table 4). When sibling effects were examined more closely using multiple pairwise comparisons, significant differences ($p<.05$) were noted for all but one between sibling comparison; namely T1 - T2 for F2 vowel onset (see Table 4). These results replicate earlier reports on the same speech samples (Whiteside & Rixon, 2000, 2001).

F2 locus equations

The slope, y-intercept and R-squared values representing the locus equations for T1, T2 and S are given in Table 5 for all places of articulation. Scatterplots of F2 mid vowel values (Hz) plotted against F2 onset values for all places of articulation are depicted in Figure 3 for T1, T2, and S. In addition, separate scatterplots representing F2 locus equation functions for the bilabial, alveolar, velar and glottal places of articulation are depicted in Figures 4a, 4b, 4c and 4d, respectively for T1, T2 and S. The order of the steepness of the slope values was the same for T1 and T2. This was as follows: glottal > bilabial > velar > alveolar. A slightly different order of steepness of slope values was found for S, which was as follows: glottal > velar > bilabial > alveolar. The slope values for T1, T2 and S for bilabial, alveolar and velar places of articulation are within the range of those published elsewhere (Sussman, McCaffrey & Matthews, 1991; Sussman, Dalston & Gumbert, 1998). The order of slopes for bilabial, alveolar and velar places of articulation presented by T1 and T2 is in line with 18/20 of the speakers reported by Sussman and colleagues (Sussman, McCaffrey & Matthews, 1991), while the order of slopes for S agree with those of the remaining 2 speakers from the same study. Higher slope values reflect higher levels of coarticulation for those consonants which display greater levels of covariation between F2 onset and F2 mid/target values, and therefore higher levels of coarticulation. For example, in the cases of both /b/ and /h/, the articulators of the consonants are independent of the tongue. The lingual gestures for the vowels can therefore be anticipated to a greater extent in the /bVC/ and /hVC/ syllables compared to /dVC/ because /d/ involves lingual gestures. This therefore explains why the slope values for /b/ and /h/ are higher than slopes for /d/ in the data of all three siblings (see Table 4). However, the slight difference in the order of slopes for S between deserves some discussion. Here, slightly higher slope values were found for /g/ (.89) compared to those for /b/ (.86), which suggests that overall levels of F2 onset and F2 target covariation were slightly higher for /g/ compared to /b/. It is also worth highlighting however, that T2 displayed a slope value for /g/ of .88 which is comparable to that observed for S (see Table 4). In addition, all three speakers displayed the greatest level of variability in the slope data for the velar data set compared to the other places of articulation (see 95% CI data in Table 4), suggesting that there was greater allophonic variation in covariation between the F2 onset and F2 target values for the small vowel repertoire represented by the word tokens.

The y-intercept values for T1, T2 and S showed the same order of values by place of articulation: glottal < bilabial < velar < alveolar. The y-intercept values for T1, T2 and S for bilabial, alveolar and velar places of articulation are within the range those published elsewhere (Sussman, McCaffrey & Matthews, 1991; Sussman, Dalston & Gumbert, 1998). The lower y-intercept values for /h/ and /b/ are indicative of higher levels of coarticulation compared to the appreciably higher y-intercept values observed for /d/ which reflect lower levels of articulation, reasons for which were discussed above (see Table 4 for y-intercept values). It also worth commenting at this point that the y-intercept values for /g/ displayed high levels of variation (see 95% CI data in Table 4). This reinforces the suggestion that the velar data set displayed high levels of allophonic variation in a data set which represents a modest vowel repertoire. High levels of variation in the y-intercept values for /g/ are documented elsewhere (Sussman, McCaffrey & Matthews, 1991; Sussman, Dalston & Gumbert, 1998).

Figure 5 depicts a higher order acoustic space expressed in terms of the slope values plotted against normalised y-intercept values for all 4 places of articulation for T1, T2 and S. Figure 6 illustrates the Euclidean distances between T1 and T2, T2 and S, and T1 and S in the higher order acoustic space shown in Figure 5. If we scrutinise the between sibling differences by place of articulation, we see further evidence of greater similarities between the twins, with the smallest distances being observed between T1 and T2 for alveolar, bilabial and glottal places of articulation. This contrasts with the velar place of articulation, where the smallest distance was found between T2 and S, a fact which is reflected in the slope and y-intercept values that are provided in Table 5. Figure 7 gives Euclidean distance plots connecting higher order acoustic space coordinates for /b/, /d/, /g/ and /h/, and highlights in detail between sibling comparisons for T1 and T2 (Figure 7 (a)), T1 and S (Figure 7 (b)), and T2 and S (Figure 7 (c)). From Figure 7 we can see that this higher order acoustic space appears most similar for T1 and T2 (Figure 7 (a)), and least similar for T1 and S (Figure 7 (b), a result which is mirrored by the results of the Chow tests (see below). The Euclidean distances between consonant pairs (/b-d/, /d-g/, /g-h/, /h-b/) for each sibling represented in Figure 7 are provided in Table 6 together with the total perimeter values of this higher order acoustic space. The data provided in Table 6 (see also Figure 7(c)) highlight the greater similarity between T2 and S for the Euclidean distance between /d/and /g/ due to the similarities in their slope and y-intercept values for /g/ as discussed above (see also Table 5). However, the general trends in the data provided in Table 6 and Figure 7 depicting the Euclidean distances across all consonant pairs (/b-d/, /d-g/, /g-h/, /h-b/) illustrate that the perimeter values for T1 (1.93) and T2 (1.75) are marginally more similar than those for T2 (1.75) and S (1.54), and least similar for T1 (1.93) and S (1.54).

Testing for between sibling differences: Chow tests

Table 7 gives the results of four sets of Chow tests which were used to test for between sibling differences in the regression functions expressing the relationship between the mid vowel and vowel onset values of F2 as a measure of coarticulation. Model 1 examined whether the twins' data could be pooled. Results showed that the regression functions for T1 and T2 representing F2 coarticulation patterns can be pooled for each place of articulation (see Model 1 in Table 7). Model 2 examined whether the twins' data could be pooled with those of their sibling (S). Significant differences indicated that this was not the case for any place of articulation, therefore suggesting that the combined data for the twins could not be pooled with those of their sibling for any place of articulation (see Model 2 results in Table 7). Model 3 examined whether the data modelled by the regression functions for T1 and S could be pooled. Results showed significant differences for all but one place of articulation (glottal), therefore suggesting that the data for T1 and S could only be pooled for the glottal place of articulation (see Model 3 results in Table 7). Model 4 examined whether the regression functions for T2 and S could be pooled. Results showed significant differences for the bilabial and alveolar data, therefore indicating the data for T2 and S could only be pooled for both velar and glottal places of articulation (see Model 4 results in Table 7).

In summary, 4/4 of the Chow tests for Model 1 were not significant compared to 0/4, 1/4, and 2/4 for Models 2, 3 and 4, respectively (see Table 7). This therefore suggests greater similarity between the twins data compared to their age- and sex-matched sibling.

DISCUSSION

If we examine the changes between F2 onset and F2 target values on a token by token basis for all three siblings as one method of characterising coarticulation patterns, it is difficult to identify the overall levels of similarity between each sibling pair, and we are also made aware of the level of variability that exists for each sibling, and for each token (see results section). Whilst acknowledging that F2 locus equations may not fully represent individual speaker variability and the level of phonetic-context determined variation one sees on a token by token basis (see Table 3, and results section above), they move beyond the level of the individual token and allow the linear parameterisation of F2 onset and F2 target values for larger sets of data. Furthermore, this linear parameterisation provides us coarticulation indices. This preliminary study aimed to investigate the speech patterns of a set of adult male monozygotic twins and an age-matched same sex sibling using read speech samples. F2 onset and F2 target values and coarticulation patterns were examined using F2 locus equations for 4 consonants (/b/, /d/, /g/ and /h/) in CV sequences.

Speech patterns of MZ twins

Based on the results of previous studies (Locke & Mather, 1989; Matheny & Bruggemann, 1972, 1973; Nolan & Oh, 1996; Przybyla, Horii & Crawford, 1992), it was predicted that the twins would display a greater degree of similarity and convergence in their formant frequency values and coarticulation patterns compared to their age- and sex-matched sibling. Based on their respective heights and weights (see Table 1), it is not unreasonable to suggest that all 3 siblings had similar vocal tract lengths. However, the twins displayed higher F2 onset and F2 target (mid) values compared to their age- and sex-matched sibling (see Table 3 and Figure 2), which suggests that there may have been greater physical similarities between the vocal tracts of the twins compared to their sibling. However, further physical evidence would be necessary to explore this possibility further. The F2 onset and F2 target data for all three siblings displayed variation which was conditioned by phonetic context (see Table 3, Figure 2 and results section).

In addition, the twins displayed some evidence of higher levels of similarity in their coarticulation parameters compared to their sibling. This greater overlap in their coarticulation patterns was demonstrated by a number of different measures and statistical evaluations which are summarised as follows. Firstly, F2 vowel onset values highlighted a greater degree of similarity between the twins (see Table 4). From this data, it could be inferred that the twins may have used similar articulatory dynamics at the onset of vowels in the CV sequences with respect to the anterior-posterior lingual gestures indexed by F2. Alternatively, the already posited suggestion of greater physical similarity in their vocal tracts could explain these data. Secondly, the F2 locus equations (see Table 5 and Figures 3 and 4) and the Chow tests (see Table 7) which tested for between sibling differences in the relationship between F2 mid vowel and F2 vowel onset values of all three siblings indicated a larger number of similarities between the twins compared to other between-sibling comparisons. Finally, when the "higher order acoustic space" of the F2 mid vowel/vowel onset relationship expressed in terms of the slope and normalised y-intercept values was examined, the twins were found, for the most part, to display greater similarities compared to their age- and sex-matched sibling. For example, the smallest values for between sibling Euclidean distance comparisons for bilabial, alveolar and glottal places of articulation were found for T1 and T2 (see Figures 5 and 6) suggesting that they had similar patterns of coarticulation in the CV sequences of the consonants /b/, /d/ and /h/. In addition, the Euclidean distances between consonant pairs (/b-d/, /d-g/, /g-h/, /h-b/)for between sibling comparisons (Figure 7) showed higher levels of similarity for T1 and T2 compared to the other between sibling comparisons, and marginally greater similarities in their total perimeter values (see Table 6).

Genetic and environmental influences on speech characteristics

Given the fact that all 3 siblings share the same phonological system as well as shared environmental influences, the greater overlap in the coarticulation patterns of the MZ twins suggests that their speech patterns as reflected by the coarticulation parameters investigated here may be under some degree of genetic control. Genetic influences will not only apply to the anatomical and physiological components of speech production and speech perception mechanisms, but they may apply also to those cortical areas which subserve speech and language input and output processes (Thompson, Cannon, Narr, van Erp, Poutanen, Huttunen, Lönnqvist, Standertskjöld-Nordenstam, Kaprio, Khaledy, Dail, Zoumalan & Toga, 2001). Studies have found that both verbal ability (Plomin, DeFries, McClearn & Rutter, 1997; Thompson, Cannon, Narr, van Erp, Poutanen, Huttunen, Lönnqvist, Standertskjöld-Nordenstam, Kaprio, Khaledy, Dail, Zoumalan & Toga, 2001), and speech and language disorders (Lewis & Thompson, 1991, 1992; Flipsen, Shriberg, Weismer, Karlsson & McSweeney, 2001; Shriberg, Flipsen, Karlsson & McSweeney, 2001) appear to be genetically influenced. The role of genetic factors, and the extent of their impact upon the cortical areas which subserve speech and language processing, and the acquisition of speech skills therefore deserves further investigation.

Given the extent of genetic influences on the peripheral structures involved in speech production such as the vocal tract and the larynx, it is perhaps not surprising these higher levels of physical similarity will have some influence on shaping the speech characteristics of MZ twins. Indeed the greater level of similarity between the formant frequency values of the twins seems to provide some support for this suggestion (see Figure 2). In addition, the coarticulation patterns represented by the F2 locus equations reported in this study suggest that although there is some degree of family resemblance in the speech characteristics of all three siblings (T1, T2, and S), the extent of the similarities is greatest between MZ twins (T1 and T2). These findings taken as a whole suggest that the genetic influences between the twins may be greater than those of their sibling. They suggest a cascade of genetic influences on speech characteristics, and parallel the findings of a brain imaging study where a genetic continuum was found in the brain structures of MZ twins (highest degree of overlap and similarity), DZ twins and unrelated subjects (lowest degree of overlap and similarity) (Thompson, Cannon, Narr, van Erp, Poutanen, Huttunen, Lönnqvist, Standertskjöld-

Nordenstam, Kaprio, Khaledy, Dail, Zoumalan & Toga, 2001). More data from a larger cohort of twins and related individuals are necessary to further explore the role of genetic factors in speech characteristics and speech production skills.

Perceptual relevance of coarticulation patterns: implications for shared learning capacity?

There is direct evidence from perceptual studies which supports the role of genetics in perceptual processing abilities for both speech (Jäncke and Steinmetz, 1994) and musical stimuli (Drayna, Manichaikul, de Lange, Sneidor & Spector, 2001). There is some debate about the perceptual relevance of coarticulation patterns parameters such as F2 locus equations (see Sussman, Fruchter, Hilbert & Sirosh, 1998 for a review and commentaries). However, developmental studies (Sussman, Minifie, Buder, Stoel-Gammon & Smith, 1996; Sussman, Duder, Dalston & Cacciatore, 1999), and perceptual studies using synthetic stimuli (Sussman, Fruchter & Cable, 1995) suggest that the acoustic parameters they represent may play some role in the perception of stop consonants. Furthermore, F2 locus equations remain stable even under articulatory perturbation (Sussman, Fruchter & Cable, 1995). This suggests that speakers will compensate during articulatory perturbation in order to maintain the acoustic cues and therefore, the auditory cues for consonants signaled by the lawful relationship (transition or frequency change) between the onset and target values of vowels in CV(C) syllables (Sussman, Fruchter & Cable, 1995). The perceptual relevance of F2 locus equations and their characterization of coarticulation patterns and the role of genetic factors in both perceptual abilities and the acquisition of motor speech skills therefore deserves further investigation.

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REFERENCES

Chow, G. C.: Tests of equality between sets of coefficients in two linear regressions. Econometrica *28:* 591-605 (1960).

Duez, D.: Second-formant locus patterns: An investigation of spontaneous French speech. Speech Commun. *11:* 417-427 (1992).

Drayna, D.; Manichaikul, A.; de Lange, M.; Snieder, H.; Spector, T.: Genetic correlates of musical pitch recognition in humans. Science *291*: 1969-1972 (2001).

Fairbanks, G.: Voice and articulation drillbook (2nd ed.). (Harper and Bros, New York 1960).

Fitch, W. T.; Giedd, J.: Morphology and development of the human vocal tract: a study using magnetic resonance imaging. J. acoust. Soc. Am. *106*: 1511-1522 (1999).

Flipsen, Jr., P.; Shriberg, L. D.; Weismer, G.; Karlsson, H. B.; Mc Sweeney, J. L.: Acoustic phenotypes for speech-genetic studies: reference data for residual /ɝ/ distortions. Clin. Ling. Phonet. *15*: 603-630 (2001).

Forrai, G.; Gordos, G.: A new acoustic method for the discrimination of monozygotic and dizygotic twins. Acta Paed. Hung. *24:* 315-321 (1983).

Foulkes, P.; Docherty, G. Urban voices: accent studies in the British Isles. (Arnold, London 1999).

Fruchter, D.; Sussman, H. M.: The perceptual relevance of locus equations. J. acoust. Soc. Am. *102:* 2997-3008 (1997).

Fuchs, M.; Oeken, J.; Hotopp, T.; Täschner, R.; Hentschel, B.; Behrendt, W.: Similarity in monozygotic twins regarding vocal performance and acoustic features and their possible clinical relevance. HNO *48:* 462- 469 (2000).

Hay, D. A.; Prior, M.; Collet, S.; Williams, M.: Speech and language development in preschool twins. Acta Genet. Med. Gemellolog. *36:* 213-223 (1987).

Hohnen, B.; Stevenson, J.: The structure of genetic influences on general cognitive, language, phonological and reading abilities. Dev. Psych. *35:* 590-603 (1999).

Jäncke, L.; Steinmetz, H.: Auditory lateralization in monozygotic twins. Int. J. Neuroscience *75:* 57-64 (1994).

Krull, D.: Second formant locus patterns and consonant-vowel coarticulation in spontaneous speech. Phonetic Experimental Research at the Institute of Linguistics, University of Stockholm, Perilus *10:* 87-108 (1989).

Lenneberg, E. H.: Biological foundations of language. (John Wiley & Sons, New York: 1967).

Lenneberg, E. H.: On explaining language. Science *164:* 635-643 (1969).

Lewis, B. A.; Freebairn, L.: Speech production skills of nuclear family members of children with phonology disorders. Lang. Speech, *41*: 45-61 (1997).

Lewis, B. A.; Thompson, L. A.: Speech and language disorders in twins. Beh. Genet. *21:* 577-577 (1991).

Lewis, B. A.; Thompson, L. A.: A study of developmental speech and language disorders in twins. J. Speech Hear. Res. *35,* 1086-1094 (1992).

Lindblom, B.: On vowel reduction. Report 29, Speech Transmission Lab. Royal Inst. Technol. Stockholm, Sweden (1963).

Locke, J. L.; Mather, P. L.: Genetic factors in the ontogeny of spoken language: evidence from monozygotic and dizygotic twins. Child Lang. *16:* 553-559 (1989).

Maddala, G. S. Introduction to Econometrics. (John Wiley and Sons, Chichester 2001).

Matheny, A. P.; Bruggemann, C. E.: Articulation proficiency in twins and singletons from families of twins. J. Speech Hear. Res. *15:* 845-851 (1972).

Matheny, A. P.; Bruggemann, C. E.: Children's speech: heredity components and sex differences. Folia Phoniatr. *25:* 442-449 (1973).

Mather, P. L.; Black, K. N.: Heredity and environmental influences on preschool twins' language skills. Dev. Psych. *20:* 303-308 (1984).

Mittler, P.: Language development in young twins: biological, genetic and social aspects. Acta Genet. Med. Gemellolog. *25:* 359-365 (1976).

Munsinger, H.; Douglas, A.: The syntactic abilities of identical twins, fraternal twins, and their siblings. Child Dev. *47,* 40-50 (1976).

Nearey, T. M.; Shammass, S. E.: Formant transitions as partly distinctive invariant properties in the identification of voiced stops. Can. Acoust. *15*, 17-24 (1987).

Nolan, F.; Oh, T.: Identical twins, different voices. Forensic Ling. *3*: 39-49 (1996).

Plomin, R.; DeFries, J. C.; McClearn, G. E.: Behavioral genetics: a primer (2nd Edition) (W. H. Freeman, New York 1990).

Plomin, R.; DeFries, J. C.; McClearn, G. E.; Rutter, M.: Behavioral genetics (3rd Edition). (W. H. Freeman, New York 1997).

Plomin, R.; Kosslyn, S. M.: Genes, brain and cognition. Nature Neurosci. *4 (12):* 1153-1155 (2001).

Przybyla, B. D.; Horii, Y.; Crawford, M. H.: Vocal fundamental frequency in a twin sample: looking for a genetic effect. J. Voice 3*:* 261-266 (1992).

Shriberg, L. D.; Flipsen, Jr., P.; Karlsson, H. B.; McSweeney, J. L.: Acoustic phenotypes for speech-genetics studies: an acoustic marker for residual /ɝ /distortions. Clin. Ling. Phonet. *15:* 631-650 (2001).

Spitz, R. V.; Tallal, P.; Flax, J.; Benasich, A. A.: Look who's talking: a prospective study of familial transmissions of language impairments. J. Speech Lang. Hear. Res. *40:* 990-1001 (1997).

SPSS for Windows (Version 10.0.0) [computer program]. SPSS Inc. (1999).

Stromswold, K.: Genetics of spoken language disorders. Human Biology *70:* 297-324 (1998).

Sussman, H. M.: Representation of phonological categories: a functional role for auditory columns. Brain Lang. *80:* 1-13 (2002).

Sussman, H. M.; Duder, C.; Dalston, E.; Cacciatore, A.: An acoustic analysis of CV coarticulation: a case study. J. Speech Lang. Hear. Res. *42:* 1080-1096 (1999).

Sussman, H. M.; Dalston, E.; Gumbert, S.: The effect of speaking style on a locus equation characterization of stop place of articulation. Phonetica*, 55,* 204-225 (1998).

Sussman, H. M.; Fruchter, D.; Hilbert, J.; Sirosh, J.: Linear Correlates in the speech signal: the orderly output constraint. Behav. Brain Sci. *21:* 241-299 (1998).

Sussman, H. M.; Fruchter, D.; Cable, A.: Locus equations derived from compensatory articulation. J. acoust. Soc. Am. *97:* 3112-3124 (1995).

Sussman, H. M.; Hoemeke, K.; McCaffrey, H. A.: Locus equations as an index of coarticulation for place of articulation distinctions in children. J. Speech Hear. Res. *35:* 769-781 (1992).

Sussman, H. M.; McCaffrey, H. A.; Matthews, S. A.: An investigation of locus equations as a source of relational invariance. J. acoust. Soc. Am. *90:* 1309-1325 (1991).

Sussman, H. M.; Minifie, F. D.; Buder, E. H.; Stoel-Gammon, C.; Smith, J.: Consonant-vowel interdependencies in babbling and early words: preliminary examination of a locus equation approach. J. Speech Hear. Res. *39:* 424-433 (1996).

Sussman, H. M.; Shore, J.: Locus equations as phonetic descriptors of consonants place of articulation. Perception Psychophysics *58 (6):* 936-946 (1996).

Tabain, M.: Coarticulation in CV syllables: a comparison of locus equations and EPG data. J. Phonet. *28:* 137-159 (2000).

Tabain, M.; Butcher, A.: Stop consonants in Yanyuwa and Yindjibarndi: locus equation data. J. Phonet. *27:* 333-357 (1999).

Thompson, L. A.; Detterman, D. K.; Plomin, R.: Associations between cognitive abilities and scholastic achievement: genetic overlap, but environmental differences. Psych. Sci. *3,* 158-165 (1991).

Thompson, P. M.; Cannon, T. D.; Narr, K. L.; van Erp, T.; Poutanen, V.; Huttunen, M; Lönnqvist, J.; Standertskjöld-Nordenstam, C.; Kaprio, J.; Khaledy, M.; Dail, R.; Zoumalan, C. I.; Toga, A. W.: Genetic influences on brain structure. Nature Neurosci. *4 (12):* 1253- 1258 (2001).

Whiteside, S. P.; Rixon, E.: The identification of twins from pure (single speaker) syllables and hybrid (fused) syllables: an acoustic and perceptual case study. Percept. Mot. Skills *91*: 933-947 (2000).

Whiteside, S. P.; Rixon, E.: Speech patterns of monozygotic twins: an acoustic case study of monosyllabic words. The Phonetician 84: 9-22 (2001).

Table 1. Height and weight details for T1, T2, and S.

Subject	Height (cm)	Weight (kg)
T1	183	82.6
T2	183	82.6
S	180	79.4

Table 2. Results of homogeneity of variance tests for F2 vowel onset and F2 mid vowel data based on the mean (Levene's Statistic).

Form. Freq.	Place of articulation	Model 1* (T1 & T2 pooled vs. T1, T2 values modelled separately)	Model 2* (T1 & T2 & S pooled vs T1 & T2, S values modelled separately)	Model 3* (T1 & S pooled vs. T1, S values modelled separately)	Model 4* (T2 & S pooled vs. T2, S values modelled separately)
Homogeneity of Variance Tests (Levene's statistics) based on the mean (df1, df2; F, p level)	Bilabial				
	F2 vowel onset	2, 171; .003, p=.997‡	2, 255; 1.704, p=.184‡	2, 167; 1.297, p=.276‡	2, 169; 1.309, p=.273‡
	F2 mid vowel	2, 171; .005, p=.995‡	2, 255; .054, p=.947‡	2, 167; .055, p=.947‡	2, 169; .029, p=.972‡
	Alveolar				
	F2 vowel onset	2, 203; .919, p=.401‡	2, 311; .007, p=.993‡	2, 207; .179, p=.836‡	2, 207; .179, p=.836‡
	F2 mid vowel	2, 203; .336, p=.715‡	2, 311; .814, p=.444‡	2, 207; .230, p=.795‡	2, 207; .230, p=.795‡
	Velar				
	F2 vowel onset	2, 77; .063, p=.939‡	2, 117; 1.704, p=.186‡	2, 77; 1.598, p=.209‡	2, 77; .911, p=.407‡
	F2 mid vowel	2, 77; .011, p=.989‡	2, 117; .151, p=.806‡	2, 77; .069, p=.933‡	2, 77; .148, p=.862‡
	Glottal				
	F2 vowel onset	2, 147; .004, p=.996‡	2, 225; .169, p=.844‡	2, 151; .153, p=.858‡	2, 149; .105, p=.900‡
	F2 mid vowel	2, 147; .007, p=.993‡	2, 225; .627, p=.535‡	2, 151; .511, p=.601‡	2, 149; .354, p=.703‡

* see text for description of models
‡ indicates equality of variance.

Table 3. Mean and standard deviation values for the F2 onset and F2 mid values (both in Hz) by word token and place of articulation for T1, T2 and S.

Place of articulation	Word	F2 parameter (Hz)	Subject					
Bilabial			T1		T2		S	
			Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation
	bead	F2 onset	2191.80	73.40	2185.60	164.54	2063.75	79.13
		F2 mid	2302.20	64.23	2430.80	136.08	2309.75	195.86
	bib	F2 onset	2033.00	53.22	1920.75	75.35	1805.00	52.92
		F2 mid	1943.00	145.56	1954.75	36.04	1973.00	89.60
	bid	F2 onset	2058.60	33.31	1999.20	18.43	1746.40	61.41
		F2 mid	2068.20	39.42	2000.60	53.85	1922.40	122.43
	bed	F2 onset	1774.80	141.25	1801.20	48.82	1594.80	79.55
		F2 mid	1884.40	95.93	1898.40	29.89	1741.60	46.74
	bad	F2 onset	1428.40	65.42	1460.40	78.25	1161.00	26.54
		F2 mid	1481.40	45.25	1524.60	42.62	1296.20	63.70
	bob	F2 onset	1112.00	35.79	1143.40	63.20	1089.20	20.47
		F2 mid	1127.25	82.10	1164.40	89.82	1074.20	32.75
	bored	F2 onset	830.60	91.38	851.00	47.17	774.40	27.12
		F2 mid	953.00	175.65	1038.20	124.79	851.00	113.54
	bud	F2 onset	1009.00	82.42	959.80	39.98	892.80	104.53
		F2 mid	1083.00	96.26	1123.60	64.72	974.60	64.84
	bird	F2 onset	1317.60	104.02	1139.00	45.59	1259.80	56.57
		F2 mid	1311.20	76.83	1257.40	79.53	1403.20	39.84

Table 3. continued. Mean and standard deviation values for the F2 onset and F2 mid values (both in Hz) by word token and place of articulation for T1, T2 and S.

Place of articulation	Word	F2 parameter (Hz)	Subject					
Alveolar			T1		T2		S	
			Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation
	deed	F2 onset	2192.60	87.22	2268.60	113.75	2129.80	45.18
		F2 mid	2335.20	52.55	2330.00	20.48	2371.80	96.48
	did	F2 onset	2049.60	56.07	2077.20	16.60	1847.20	40.59
		F2 mid	2045.60	41.92	1993.80	31.95	1944.80	64.43
	dead	F2 onset	2061.80	66.04	1954.20	37.86	1784.60	57.67
		F2 mid	1856.40	107.33	1911.60	41.76	1749.40	46.55
	dab	F2 onset	1801.60	60.19	1766.20	49.41	1571.00	88.90
		F2 mid	1486.60	44.74	1553.80	48.19	1402.60	90.50
	dad	F2 onset	1747.60	122.02	1758.75	38.53	1528.20	63.30
		F2 mid	1518.00	93.33	1580.25	35.00	1306.80	31.57
	daub	F2 onset	1588.75	79.21	1573.60	58.68	1491.40	132.31
		F2 mid	1077.00	31.65	1219.60	77.87	1096.20	9.86
	dog	F2 onset	1628.40	69.70	1688.60	62.92	1542.20	165.50
		F2 mid	1226.00	89.29	1317.00	178.10	1146.40	34.66
	dub	F2 onset	1543.20	78.01	1638.00	106.39	1444.80	44.73
		F2 mid	1173.83	197.54	1177.20	105.48	1062.00	43.16
	dud	F2 onset	1507.50	65.63	1631.75	139.71	1512.50	243.80
		F2 mid	1208.75	105.64	1308.25	135.99	1079.25	22.37
	dug	F2 onset	1625.80	78.47	1712.00	62.80	1458.20	45.59
		F2 mid	1133.25	70.32	1281.40	129.87	1074.00	50.25
	dude	F2 onset	1943.00	109.03	1986.60	50.83	1826.00	62.02
		F2 mid	1534.00	85.71	1720.00	191.38	1728.40	101.74

Table 3. continued. Mean and standard deviation values for the F2 onset and F2 mid values (both in Hz) by word token and place of articulation for T1, T2 and S.

Place of articulation	Word	F2 parameter (Hz)	Subject					
Velar			T1		T2		S	
			Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation
	gig	F2 onset	2205.20	50.60	2156.60	67.59	2113.00	87.56
		F2 mid	2120.80	15.48	2092.00	17.68	2098.20	72.40
	gag	F2 onset	2061.80	37.75	2003.00	68.97	1871.40	84.11
		F2 mid	1615.00	107.22	1695.40	55.00	1457.80	54.93
	god	F2 onset	1652.20	115.52	1727.20	132.89	1398.20	90.65
		F2 mid	1187.60	100.55	1403.80	95.82	1146.20	48.06
	good	F2 onset	1493.00	96.70	1293.00	199.39	1098.20	91.44
		F2 mid	1296.60	105.80	1130.80	92.15	1053.80	13.12
Glottal	heed	F2 onset	2283.00	37.80	2368.60	185.39	2277.20	64.10
		F2 mid	2304.60	21.04	2321.40	76.87	2407.60	76.86
	hid	F2 onset	2170.00	36.34	2072.75	12.89	1996.40	93.79
		F2 mid	2034.00	38.63	2025.00	73.45	1950.40	96.44
	head	F2 onset	1981.60	120.89	1967.60	29.00	1794.60	60.20
		F2 mid	1947.50	47.33	1909.20	24.95	1767.40	67.38
	had	F2 onset	1504.20	52.52	1539.00	51.60	1269.80	97.10
		F2 mid	1472.80	17.25	1566.00	65.65	1357.40	97.03
	hard	F2 onset	1469.40	62.77	1374.75	176.73	1112.40	56.07
		F2 mid	1531.80	29.56	1528.00	118.12	1285.80	113.95
	hoard	F2 onset	776.75	63.16	814.40	54.98	722.80	24.69
		F2 mid	1136.60	124.69	1014.00	94.91	869.60	135.30
	hood	F2 onset	1009.20	61.76	1059.20	29.35	881.40	146.77
		F2 mid	1141.60	93.00	1153.40	183.99	970.40	121.33
	heard	F2 onset	1348.60	59.31	1361.80	120.98	1379.00	141.54
		F2 mid	1366.80	40.30	1469.50	73.82	1481.50	57.51

Table 4. Results of a General Linear Model multivariate repeated measures testing for sibling effects for F2 vowel onset and F2 mid vowel. Mean differences between the twins (T1 and T2) and sibling (S) are also given.

Parameter	F-values for (2, 280) D.F. for within subjects (sibling) effects	Observed Power[α]	Mean difference T1 - T2 (standard error)	Mean difference T1 - S (standard error)	Mean difference T2 - S (standard error)
F2 vowel onset (Hz)	139.9†	1.0	5.9 (10.7)	169.3‡ (11.6)	163.4‡ (12.1)
F2 mid vowel (Hz)	53.5†	1.0	-34.6‡ (11.7)	90.5‡ (13.1)	125.0‡ (12.6)

†significant at p<.05

[α]Using alpha=.05

‡significant at p<.05 with Bonferroni adjustment for multiple comparisons.

Table 5. Slope, y-intercept and R-squared values representing the F2 locus equations for T1, T2 and S by place of articulation.

Place of Artic.	Parameter	T1	T2	S
Bilabial	Mean Slope	.99	.97	.86
	95% CI for Slope	.91 – 1.07	.88 – 1.05	.80 – .91
	Mean Y-intercept	-30.19	-53.55	86.58
	95% CI for Y-intercept	-169.29 – 108.92	-193.96 – 86.86	3.69 – 169.47
	R^2	.93	.93	.96
	SE	127.77	130.70	81.61
Alveolar	Mean Slope	.53	.55	.49
	95% CI for Slope	.46 –.60	.48 – .62	.42 – .55
	Mean Y-intercept	985.52	960.22	941.752
	95% CI for Y-intercept	876.31 – 1094.74	845.70 – 1074.74	843.54 – 1039.97
	R^2	.83	.83	.81
	SE	99.75	92.12	100.30
Velar	Mean Slope	.68	.88	.89
	95% CI for Slope	.46 – .89	.70 – 1.07	.69 – 1.10
	Mean Y-intercept	799.14	398.23	337.25
	95% CI for Y-intercept	453.20 – 1145.07	96.94 – 699.52	33.02 – 641.49
	R^2	.71	.85	.83
	SE	171.09	143.31	178.09
Glottal	Mean Slope	1.21	1.15	1.03
	95% CI for Slope	1.084 – 1.327	1.05 – 1.253	.94 – 1.12
	Mean Y-intercept	-380.89	-296.29	-123.00
	95% CI for Y-intercept	-584.61 – -177.17	-466.69 – -125.90	-269.21 – 23.21
	R^2	.92	.94	.93
	SE	147.82	131.46	139.95

Table 6. Euclidean distances between consonants (/b-d/, /d-g/, /g-h/, /h-b/), and total perimeter values for T1, T2 and S. Graphical illustrations representing these Euclidean distances are given in Figure 6.

	Consonant Pairs				Total perimeter of higher order acoustic space
Subject	/b-d/	/d-g/	/g-h/	/h-b/	
T1	.68	.17	.79	.28	1.93
T2	.66	.44	.44	.22	1.75
S	.57	.50	.27	.20	1.54

Table 7. Results of Chow tests for between sibling comparisons of F2 mid vowel (x) vs. F2 vowel onset (y) regression models. Model 1 compares the data of T1 and T2; Model 2 compares the combined data of T1 and T2 with those of S;

Model 3 compares the data of T1 with those of S; Model 4 compares the data of T2 with those of S (see text for further explanation).

Form. Freq.	Place of articulation	Model 1 (T1 & T2 pooled vs. T1, T2 values modelled separately)	Model 2 (T1 & T2 & S pooled vs. T1 & T2, S values modelled separately)	Model 3 (T1 & S pooled vs. T1, S values modelled separately)	Model 4 (T2 & S pooled vs. T2, S values modelled separately)
F2 mid vowel (x) vs. F2 vowel onset (y)	Bilabial	$F(2, 83)=2.39^{ns}$	$F(2, 125)=6.61$†	$F(2, 81)=10.74$†	$F(2, 82)=3.26$†
	Alveolar	$F(2, 99)=0.05^{ns}$	$F(2, 153)=24.01$†	$F(2, 101)=16.93$†	$F(2, 102)=18.30$†
	Velar	$F(2, 36)=2.36^{ns}$	$F(2, 56)=2.72$†	$F(2, 36)=4.31$†	$F(2, 36)=.45^{ns}$
	Glottal	$F(2, 71)=.24^{ns}$	$F(2, 110)=3.46$†	$F(2, 73)=3.11^{ns}$	$F(2, 72)=1.93^{ns}$

^{ns} not significant at $p<.05$, implying that the data from these groups can be pooled.
The shaded boxes highlight these non-significant data.
†significant at $p<.05$, implying that the data from these groups cannot be pooled.

FIGURE CAPTIONS

Figure 1. A wideband (183 Hz) spectrogram of 'head' indicating the sampling points for F2 vowel onset (Hz) and F2 mid vowel (Hz) data.

Figure 2. Mean values for F2 onset and F2 mid (both in Hz) for T1, T2 and S for (a) bilabial, (b) alveolar, (c) velar, and (d) glottal places of articulation. Error bars indicate +/- 1 standard error of the mean.

Figure 3. Scatterplots of F2 mid vowel values (Hz) against F2 vowel onset values (Hz) for all places of articulation (Total Population) for T1 (y=.83(x) + 370.9; R^2=.70, SE=232.09), T2 (y=.89(x) + 252.25; R^2=.74, SE=220.59), and S (y=.79(x) = 347.08; R^2=.75, SE=211.15).

Figure 4. Scatterplots for F2 mid values (Hz) against F2 onset vowel values (Hz) for bilabial, alveolar, velar, and glottal places of articulation for T1, T2 and S. See Table 4 for slope and y-intercept values.

Figure 5. Locus equation slopes plotted against normalised y-intercepts for T1, T2 and S by place of articulation in a higher order acoustic space. Table 5 gives the slope and y-intercept values that were used to plot this graph.

Figure 6. Euclidean distances between T1, T2 and S in the higher-order acoustic space by place of articulation, expressed in terms of the slope and normalised y intercept values illustrated in Figure 5.

Figure 7. Euclidean distance plots connecting higher-order acoustic space coordinates (slope and normalised y intercept values) for /b/, /d/, /g/ and /h/. This figure highlights in greater detail, the between sibling comparisons that are illustrated in Figure 5. (a) T1 and T2: the coordinates for T1 are marked by squares and bounded by dashed lines, and those for T2 are marked by triangles and bounded by solid lines. (b) T1 and S: the coordinates for T1 are marked by squares and bounded by solid lines, and those for S are marked by circles and bounded by dashed lines. (c) T2 and S: the coordinates for T2 are marked by triangles and bounded by solid lines, and those for S are marked by circles and bounded by dashed lines.

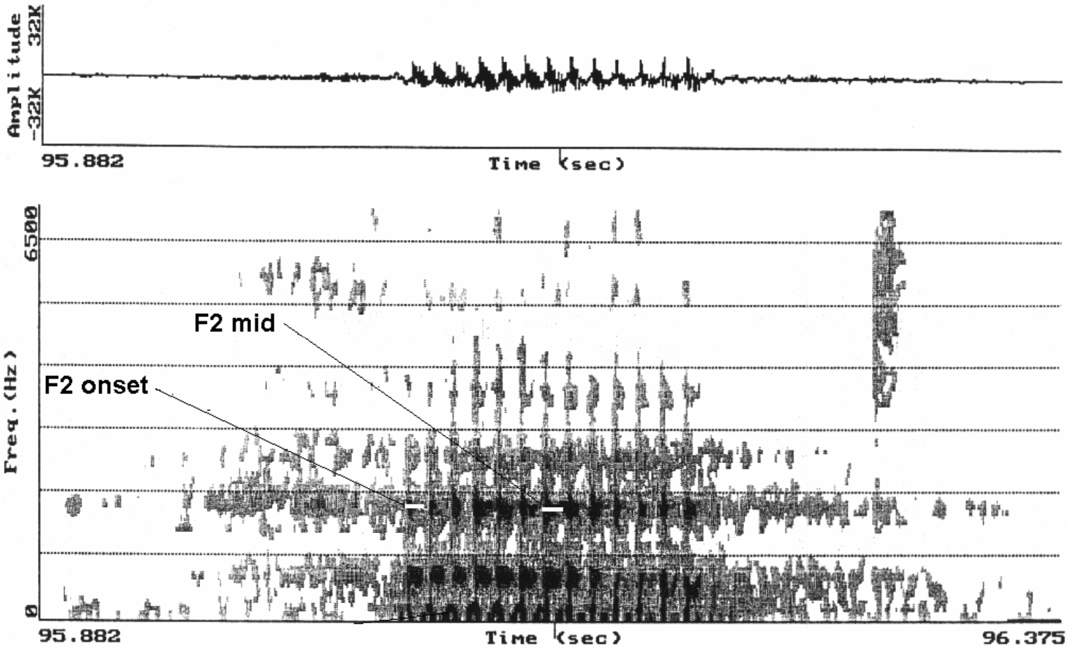
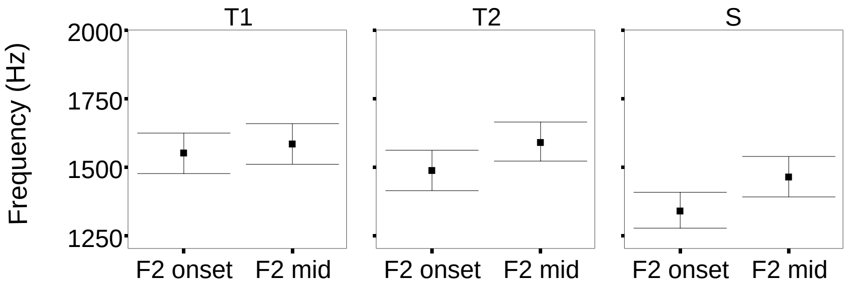
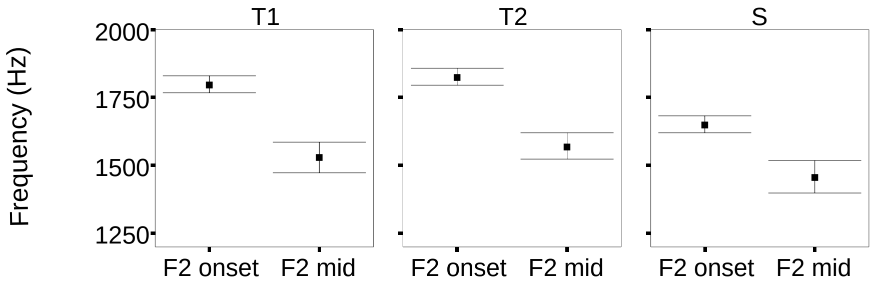

Amplitude
32K
-32K
95.882
Time (sec)
6500
Freq. (Hz)
0
F2 mid
F2 onset
95.882
Time (sec)
96.375

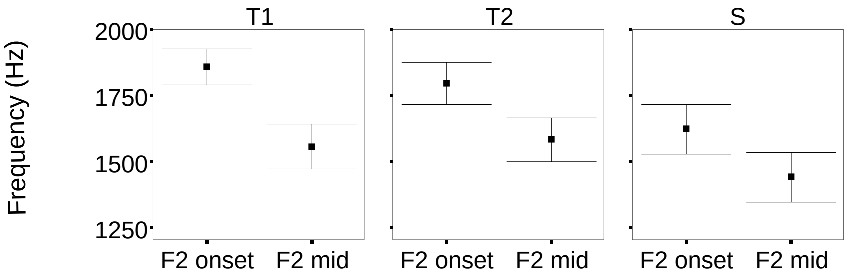
Figure 1



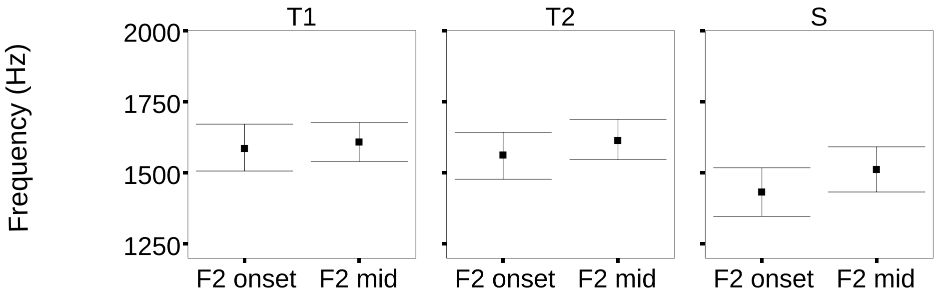
(a)



(b)

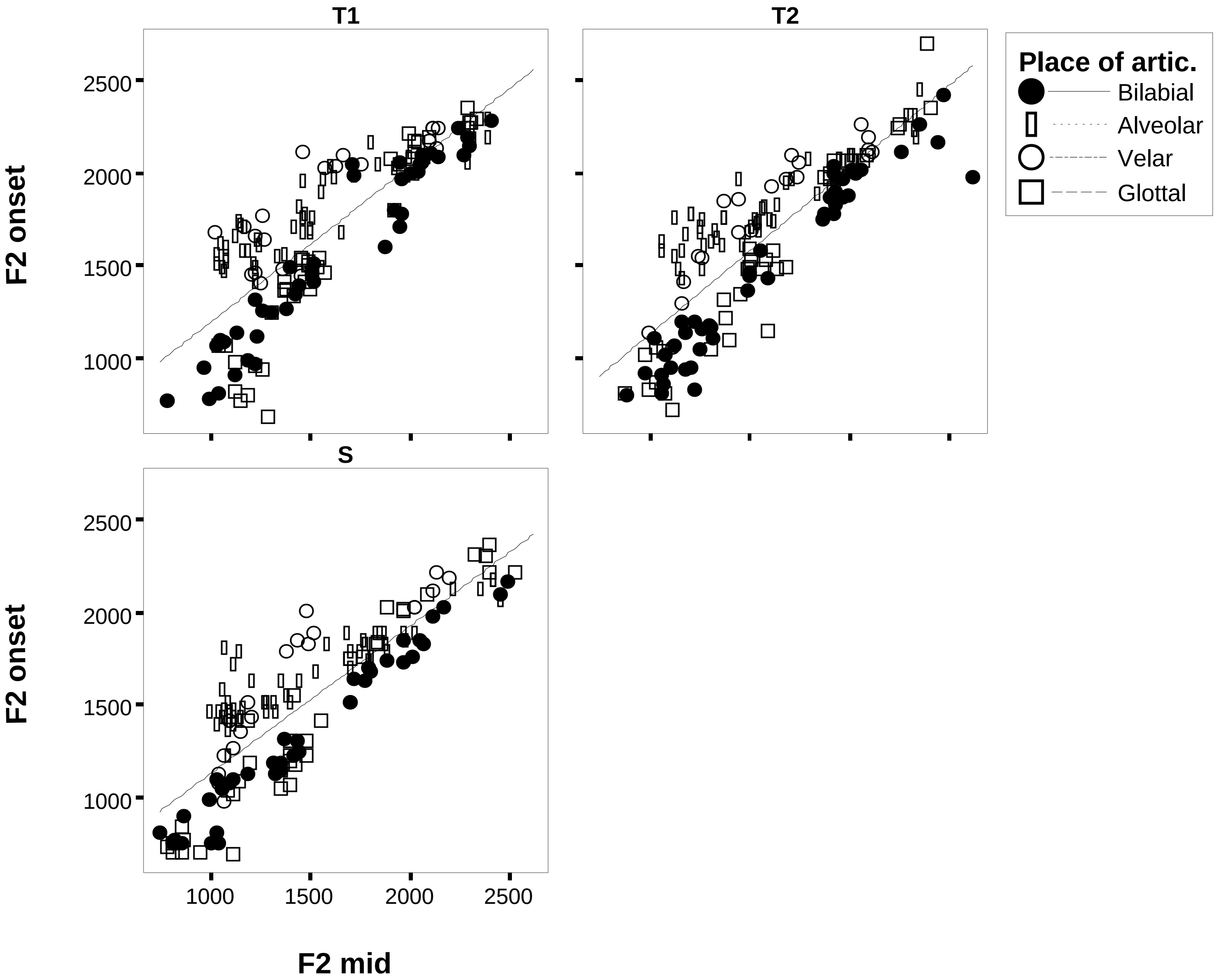


(c)



(d)

Figure 2



T1
T2
S
Place of artic.
Bilabial
Alveolar
Velar
Glottal
F2 onset
F2 onset
2500
2000
1500
1000
2500
2000
1500
1000
1000
1500
2000
2500
F2 mid

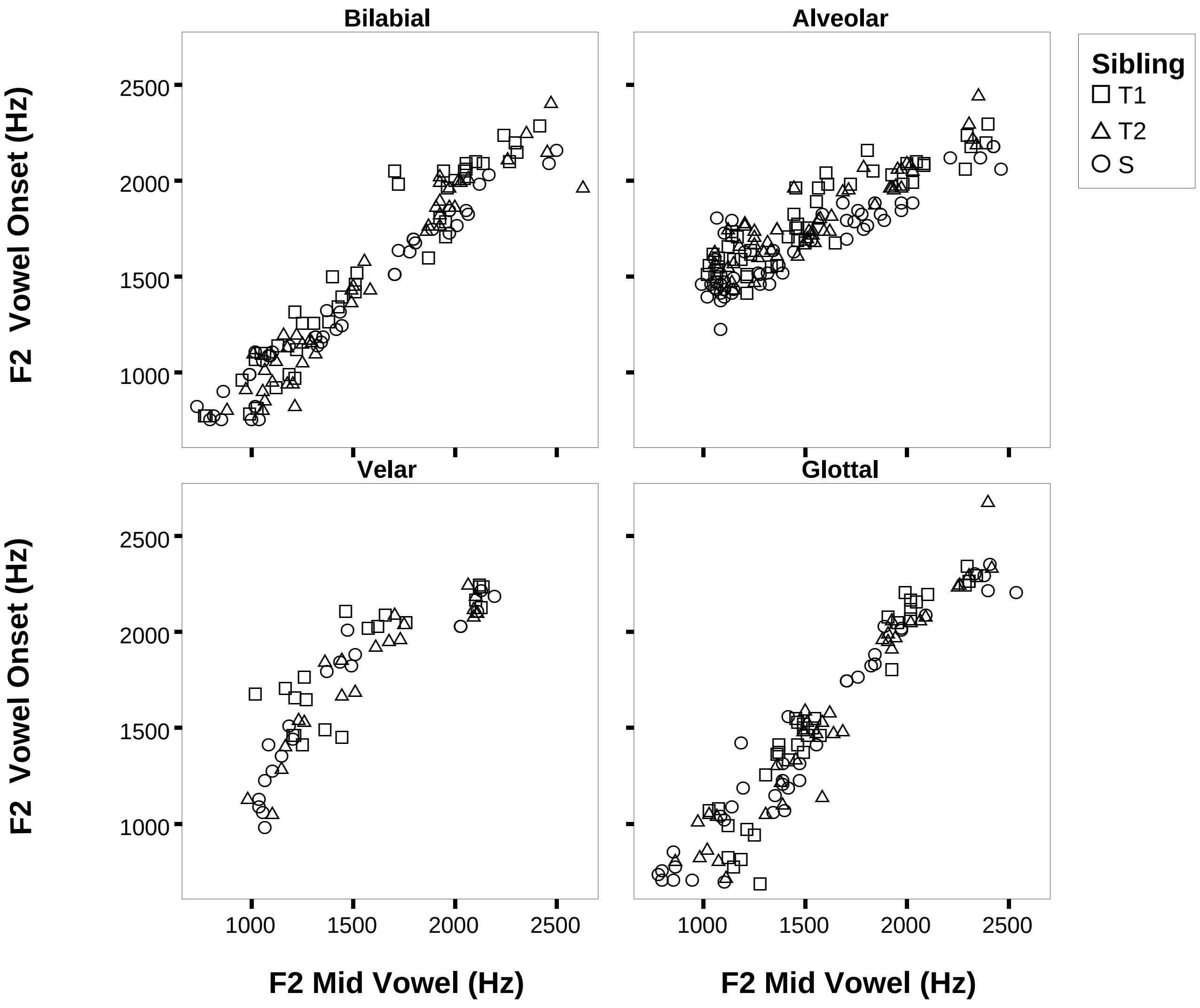

Bilabial
Alveolar
Velar
Glottal
F2 Vowel Onset (Hz)
F2 Vowel Onset (Hz)
2500
2000
1500
1000
1000
1500
2000
2500
F2 Mid Vowel (Hz)
F2 Mid Vowel (Hz)
Sibling
T1
T2
S

Figure 4

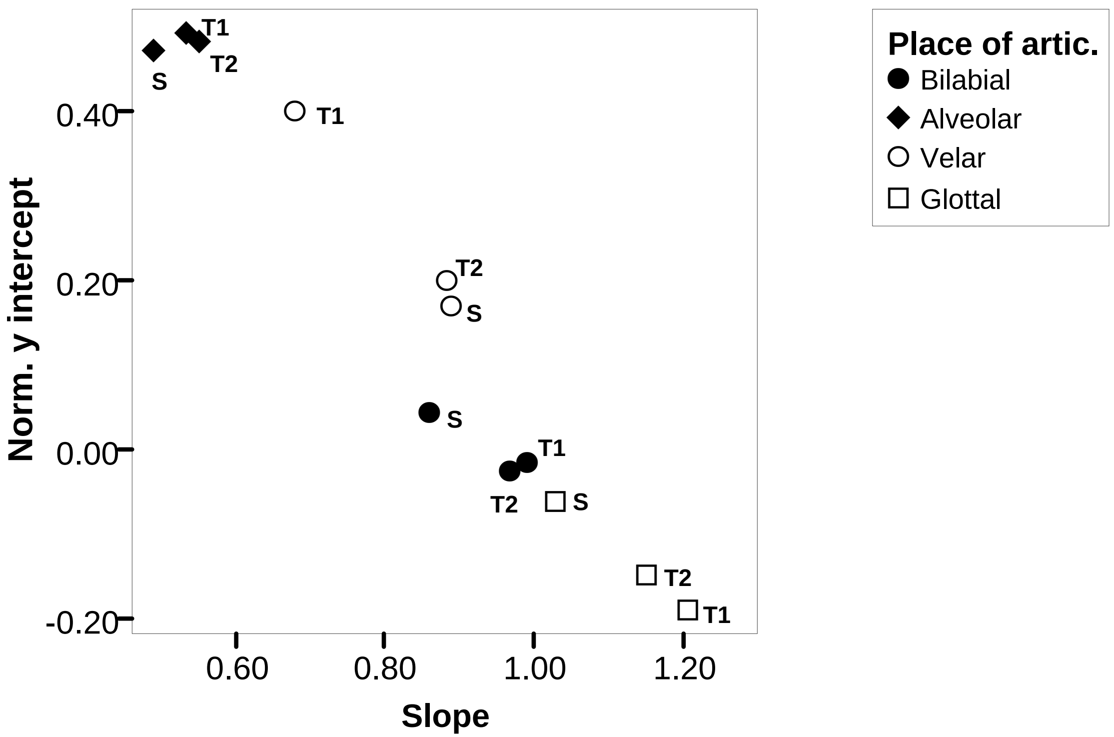

Place of artic.
Bilabial
Alveolar
Velar
Glottal
Norm. y intercept
Slope
0.40
0.20
0.00
-0.20
0.60
0.80
1.00
1.20
T1
T2
S
T1
T2
S
S
T1
T2
S
T2
T1

Figure 5

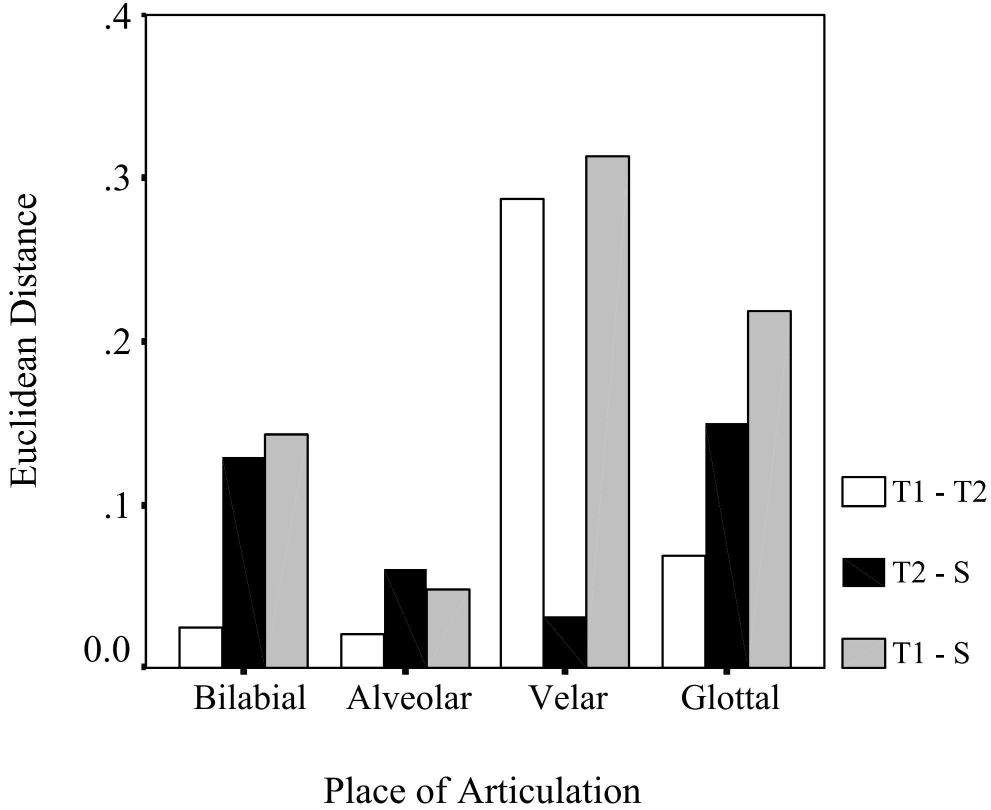
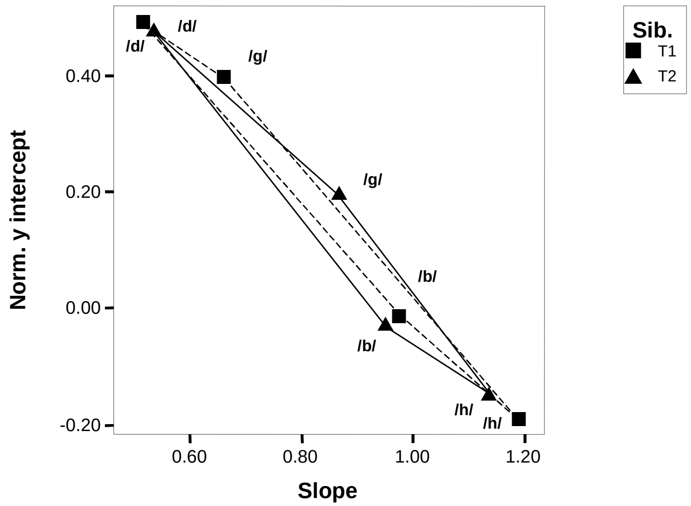
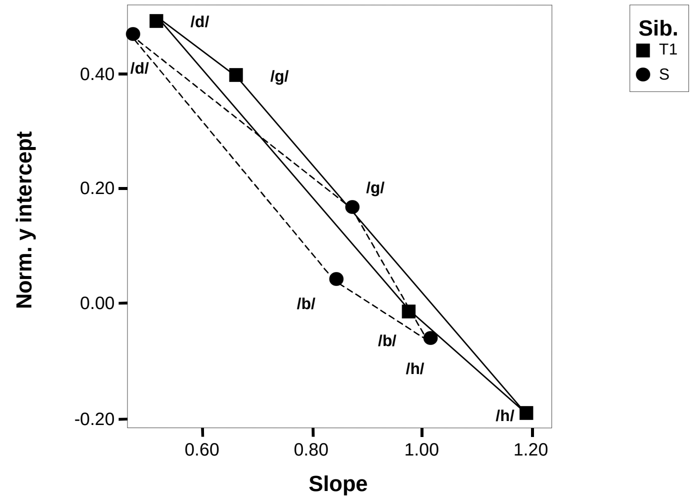

.4
.3
.2
.1
0.0
Euclidean Distance
Bilabial
Alveolar
Velar
Glottal
Place of Articulation
T1 - T2
T2 - S
T1 - S

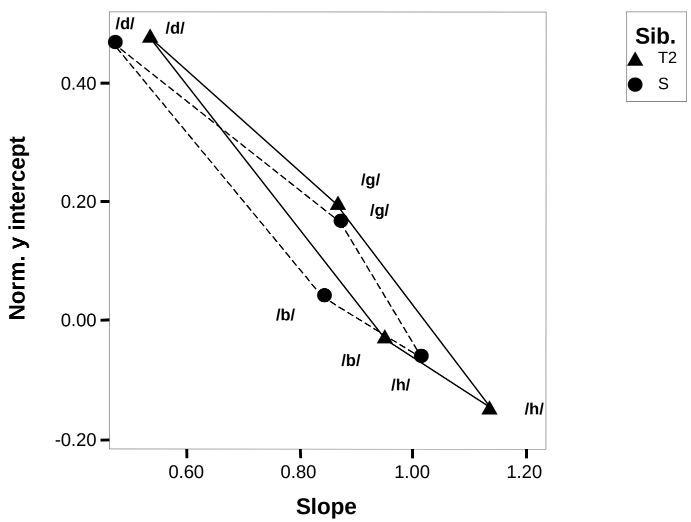
Figure 6


Norm. y intercept
Slope
Sib.
T1
T2
/d/
/g/
/b/
/h/
0.40
0.20
0.00
-0.20
0.60
0.80
1.00
1.20

(a)


Norm. y intercept
Slope
Sib.
T1
S
/d/
/g/
/b/
/h/
0.40
0.20
0.00
-0.20
0.60
0.80
1.00
1.20

(b)


Norm. y intercept
Slope
Sib.
T2
S
/d/
/g/
/b/
/h/
0.40
0.20
0.00
-0.20
0.60
0.80
1.00
1.20

(c)

Figure 7