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Developmental sexual dimorphism of the oral and pharyngeal portions of the vocal tract: An imaging study[a]

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Abstract

Purpose—The anatomic origin for prepubertal vowel acoustic differences between males and females remains unknown. The purpose of this study is to examine developmental sex differences in vocal tract (VT) length and its oral and pharyngeal portions.

Method—Nine VT variables were measured from 605 imaging studies (MRI and CT) between birth and 19 years. Given sex differences in growth rate (Vorperian et al., 2009), assessment of sex differences was done using a localized comparison window of 60 months. Analysis entailed applying this comparison window first to four discrete age cohorts, followed by a progressive assessment where this comparison window was moved in one month increments from birth across all ages.

Results—Findings document significant postpubertal sex differences in both the oral and pharyngeal portions of the VT. Also, periods of significant prepubertal sex differences in the oral region first, followed by segments in the pharyngeal region.

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Conclusions—Assessment of developmental sex differences using localized age ranges is effective in unveiling sex differences that growth rate differences may conceal. Findings on the presence of prepubertal sex differences in the oral region of the VT may clarify in part the anatomic basis of documented prepubertal acoustic differences.

I. INTRODUCTION

As the vocal tract (VT) increases in length during development, its formant frequencies decrease (Fant, 1960). Fant (1966) also noted that physiologically induced differences in formant patterns between males and females are non-uniform. In other words, relating female formant frequencies to male formant frequencies cannot be done by a simple scale factor that is inversely proportional to vocal tract length. Thus, documented acoustic differences present between adult males and females (Peterson and Barney, 1952; Fant, 1960; Childers and Wu, 1991; Zahorian and Jagharghi, 1993; Hillenbrand et al. 1995; Yang, 1996; Hagiwara, 1997; Lee, Potamianos & Narayanan, 1999; Assman and Katz, 2000; Xue and Hao 2003; and Vorperian and Kent, 2007) cannot be explained solely by differences in VT length (Fant, 1960). Indeed, acoustic differences are present during the course of development between younger males and females (e.g. Busby and Plant, 1995; Eguchi and Hirsh, 1969; Lee, Potamianos and Narayanan 1999; Perry, Ohde and Ashmead, 2001; Vorperian and Kent, 2007) even though anatomic findings to date do not indicate any evidence on prepubertal sexual dimorphism in VT structures – specifically VT length (Fitch and Giedd, 1999; Lieberman et al., 2001). Fant (1960, 1966, 1975) attributed nonuniform acoustic differences to anatomic differences in the oral versus pharyngeal portions of the VT where the pharyngeal portion is longer and the laryngeal cavity more developed in adult men as compared to women and children. King's (1952) longitudinal cephalometric data also document a longer pharyngeal length in males during the first decade of life. Apart from anatomic differences, behavioral/articulatory differences have also been suggested to be the source of prepubertal acoustic differences. Specifically Sachs, Lieberman and Erickson (1973) and P. Lieberman (1984) suggested that males tend to protrude their lips when speaking, which lengthens their VT allowing them to sound more masculine (lower formant frequencies). In addition or alternatively, VT lengthening and subsequent decrease in formant frequencies can be achieved by lowering the larynx when speaking as demonstrated by Lindblom and Sundberg's (1971) articulatory model. Such behavioral or articulatory explanations to increase VT length for the purpose of sounding more masculine, i.e. exaggerating body size, could also be of evolutionary significance (Fitch and Giedd, 1999).

The primary motivation for this study is to examine developmental anatomic differences in the oral and pharyngeal portions of the vocal tract in males versus females that could account for the observed acoustic sex differences in vowels during speech development. Drawing on 14 studies published over the past 5 decades that report data on English vowel formant frequencies, Vorperian and Kent (2007) provided a synthesis of the development of vowel acoustic space (F1-F2 and F1-F3 quadrilaterals) and concluded that sexual dimorphism emerges by age 4 years, with differences becoming more apparent by age 7 or 8 years at which age boys have consistently lower formant frequencies than girls across all vowels (Bennet, 1981; Busby and Plant, 1995; Eguchi and Hirsh, 1969; Lee et al, 1999; Perry et al, 2001; Whiteside and Hodgson, 2000). They also noted the F1-F3 patterns to have a greater developmental dispersion than the F1-F2 patterns particularly for males i.e. there is less overlap in vowel quadrilaterals over the course of development. As a good first approximation, Fant (1975) indicated that the pharyngeal cavity length is affiliated with the second formant, and the oral cavity length is affiliated with the third formant. Thus, based on cavity affiliation, it is reasonable to hypothesize that anatomic differences in oral cavity length could account for the increased developmental dispersion in F1-F3 over the course of

development. Furthermore, there are documented sex differences in craniofacial development (Enlow & Has, 2008), such as established sex-specific differences in the head circumference growth (Nellhaus, 1968; Vorperian et al. 2007) that pediatricians use clinically in the form of sex-specific growth charts. Thus, a thorough understanding of sex specific developmental changes of the VT anatomy, housed in the craniofacial complex, is warranted.

Recently, Vorperian et al. (2009) quantified the anatomic non-uniform growth of the vocal tract (VT) from a uniquely large set of imaging studies (605 imaging studies) between the ages birth to 19 years. They characterized the growth trend, growth rate and growth type (neural vs somatic) of nine VT variables including VT length, and segments within its oral and pharyngeal portions. The numeric quantification of the non-uniform growth of the VT showed differences in growth type of the oral and pharyngeal portions of the VT where the growth of the oral portion follows a predominantly hybrid or combined somatic and neural growth curve, and the pharyngeal portion follows primarily a somatic growth curve. They also presented the nonuniform growth of the VT in terms of significant sex differences in growth trend in eight of the nine variables examined with growth fits displaying sexual dimorphism past approximately age 12. Indeed, this confirms previous findings on postpubertal sexual dimorphism, (Fitch and Giedd, 1999; Lieberman et al., 2001). However, Vorperian et al. (2009) also noted the presence of prepubertal sex differences in the growth trend as well as growth rate and growth type of select variables – such as the Nasopharyngeal Length (NPhL) and Oropharyngeal Width (OPhW) – and postulated that evidence towards marked prepubertal sexual dimorphism may be masked by sex differences in growth rate. They therefore proposed a localized assessment of sex differences where the analysis would focus on limited age ranges instead of the global test they used where all ages were included. Thus, the specific purpose of this study is to assess, using localized age ranges, whether prepubertal sexual dimorphism of VT length, and segments within the oral and pharyngeal portions of the VT, is present during the course of development.

II. METHODS

A. Subjects

The imaging studies used in this study included 605 head and neck imaging studies (307 MRI and 298 CT) of typically developing individuals (327 males and 278 females) between the ages birth to 19 years. As described in Vorperian et al. (2009), the images used were from a uniquely large imaging database developed retrospectively, following Institutional Review Board (IRB) approval, of individuals who were imaged for medical reasons – such as pain or infection in the head, neck, or facial regions – considered very unlikely to affect growth and development; and where the VT structures could be clearly visualized. The images were representative of the developmental age range, with comparable distribution of males and females per age/year. Also, the weights of the majority of imaged individuals, as per the Center for Disease Control and Prevention (2000) growth curves, were at the 50^{th} percentile reference growth curves for boys and girls, with all cases falling between the 25^{th} to 95^{th} percentiles.

B. Procedures

Image Acquisition—Measurements were obtained from both MRI and CT imaging studies of the head (307 MRI & 297 CT). The image acquisition procedures have been previously described for MRI (Vorperian et al., 1999; 2005), and for CT (Vorperian et al., 2009); and for both CT and MRI in Durtschi et al. (2009). To summarize, the head and neck imaging studies were performed in supine position with the subject's head/face placed centrally in the scanner using the laser lights of the scanner with the neck in the neutral

position; and as guided by the scout image. Neutral neck position entailed adjusting the head tilt to ensure that the Reid base line (reference line from infraorbital rim to external auditory canal) was perpendicular to the table top i.e. axial scans were acquired parallel to the Reid base line. The head was held in position by foam sponges placed between the head holder and the patient's head, and all images were acquired during quiet respiration. Essentially all pediatric subjects, particularly those less than age 10 years, were sedated using either chloral hydrate 50 mg/kg administered orally, or DPT (Demerol, Phenergan, and Thorazine), or Propofol, Midazolam, Atropine, or Fentanyl administered intramuscularly (1 mg/kg), prior to the imaging study.

The in-plane image resolution of the sagittal slices used in this study varied and was in the range of 0.58 to 1.17 mm for MRI, and 0.29 to 0.59 mm for CT as determined by the ratio of field of view (FOV) divided by the matrix. The MR images were obtained using either a General Electric or Resonex MR scanner with a head receiver coil. T1 and T2-weighted images were obtained using spin-echo and fast spin-echo pulse sequences in sagittal, axial, and coronal planes with slice thickness of 2.5 – 5.0 mm, FOV in the range of 15 to 30 cm, and square matrix size of 256 or 512. The CT images were obtained using several different models of General Electric multi-slice helical CT scanners. The CT scans were acquired directly in the axial plane with a 1.25 mm slice thickness. The axial images were reconstructed with a matrix size of 512 X 512 using two different algorithms to provide a standard and a bone plus image sets. The standard image set being optimized for soft tissue detail, and the bone plus image set optimized for bone detail. The axial images were then used to generate multiplanar reformatted images in the sagittal and coronal planes with a 2–3 mm slice thickness from the thoracic inlet, inferiorly, to the top of the orbits, superiorly using a 15–30 cm FOV. The images were first stored on a McKesson Horizon Rad Station PACS system. Next, the images were set anonymous – using a General Electric Advantage Windows workstation – prior to saving the entire study in DICOM format for image analysis and data acquisition.

Data Acquisition—The software eFilm (by Merge eFilm) was used to open the DICOM file for slice selection. The midsagittal slice was used in this study for data acquisition/measurements of the variables as defined below. Midsagittal slice selection was based on the visualization of distinct cerebral sulci extending to the corpus callosum; also, the visibility of the fourth ventricle, the full length of the cerebral aqueduct of Sylvius, the pineal gland, the pituitary gland and stalk, medial part of the optic chiasm, the brainstem, and the cervical spinal cord. For CT studies, midsagittal slice selection was based on the use of both the standard and bone algorithms of the same slice. Neutral neck position was verified by assessing collinearity of the posterior margins of the vertebral bodies of C2, C3 and C4 (Shorten et al., 1994). The measure used to control for cervical spine flexion or extension was the angle subtended by two lines, the first drawn tangential to the posterior margins of C2 and C3, and the second drawn tangential to the posterior margins of C3 and C4, where an angle in the range of 180 degrees reflected a neutral neck position.

The measurements of the variables as defined below were made from the selected midsagittal slices using the software SigmaScan Pro by SYSTAT (formerly SPSS and Jandel Scientific) which was calibrated for each case/slice using the hash mark scale present on each slice of the imaging study. Measurements were made using a standardized protocol where first anatomic landmarks were placed independently by two researchers. Next, the two sets of landmarks were compared and discrepancies resolved by a radiology medical expert as needed. Then, a final or master set of landmarks was generated from which measurements were made of all the variables that could be clearly visualized. For CT images, landmarks were placed on the midsagittal slice of the bone algorithm while making reference to the standard algorithm of the same slice. Given the developmental nature of this

study, the use of this landmark placement protocol was necessary as it improved measurement accuracy. Details are given in Vorperian et al. (2009). The additional step of having master landmarks before making measurements improved the accuracy of the measurements between 82% and 100% as measured by reduction in error variability, i.e. sample variance, for all 58 variables measured in our research study. The average improvement of 58 variables is 98%. Measurement differences between the two researchers for all the variables with linear measurements was in the range of 0.00071 to 0.261 cm, and for the variables used specifically in this study the differences were less than 0.054 cm.

The CT and MRI data were combined for increased statistical power after comparing the two sets of data from 26 cases that had both MRI and CT studies in less than a three-month interval. The sex comparison analyses included only one of the duplicate MRI and CT studies that was randomly selected. The measurement discrepancy between CT and MRI for the variables used in this study were not significant as determined by paired t-tests (p-value > 0.05) with an absolute error in the range of .45 to 1.11 mm and thus compatible with image resolution (Durtschi et al. 2009).

Variables—The nine variables used in this study are depicted in Figure 1, and are the same as those used in Vorperian et al. (2009). The variables were measured in the cm unit, and reflect either direct measurements from the midsagittal slice, or derived from those direct measurements. The nine variables, numbered in parentheses prior to variable name and definition, include: (1) *Vocal tract Length (VTL)* defined as the curvilinear distance along the midline of the tract starting at the glottis – the level of true vocal folds – to the intersection with a line drawn tangentially to the lips (curvilinear distance from points J to D in Figure 1). Variables in the vertical plane included: (2) *Vocal Tract-Vertical (VT-V)* defined as the vertical distance from the glottis to the palatal plane (A-to-B plane or the ANS-PNS plane that extends from the Anterior Nasal Spine to the Posterior Nasal Spine; vertical distance from point I-to-C in Figure 1). This VT-V distance consisted of the two segments (3) *Posterior Cavity Length (PCL)* defined as the vertical distance of a line drawn from the glottis to the intersection with the end of the oral or anterior cavity length (ACL; distance I-to-G in Figure 1). Also, (4) *Nasopharyngeal Length (NPhL)* defined as VT-V minus PCL (Distance G-to-C in Figure 1). In addition, variables in the horizontal plane included (5) *Vocal Tract-Horizontal (VT-H)* defined as the horizontal distance from a line tangential to lips to the posterior pharyngeal wall (horizontal distance D-to-H in Figure 1). This VT-H distance consisted of three segments: (6) *Lip Thickness (LTh)* defined as the distance, at the level of the stomion, between two lines, the first of which is drawn tangential to the anterior aspect, and the second to the posterior or buccal aspect of the maxillary and mandibular lips (distance D-to-E in Figure 1). (7) *Anterior Cavity Length (ACL):* The horizontal distance of a line drawn from the central incisor (lingual surface, start of the hard palate) to the intersection with the vertical line drawn from the glottis to the A-to-B palatal plane (distance F-to-G in Figure 1). Also, (8) *Oropharyngeal Width (OPhW):* VT-H minus LTh minus ACL (distance G-to-H in Figure 1). Finally, another horizontal segment was calculated (9) *Vocal Tract-Oral (VT-O):* VT-H minus LTh (distance E to H in Figure 1).

C. Statistical Analysis

Assessment of sex differences during the course of development, for the nine variables defined above, was addressed using a localized comparison window of 60 months following the removal of outliers from the data as specified in Table I. Outliers removal, as specified in Vorperian et al. (2009), included removal of measurements exceeding ±2.576 σ where the probability of false removal of data is less than 0.01. Window size was determined empirically to ensure that the localized comparison has an adequate average number of subjects/observations, and yields p-values that are interpretable i.e. not too noisy. This

comparison window to assess male versus female differences entailed the use of two sample t-tests, applied in two different ways. First, it was applied to four discrete age cohorts: Cohort I – ages birth to 4;11 (4 years 11 months); Cohort II – ages 5;00 to 9;11; Cohort III, ages 10;00 to 14;11; and Cohort IV – ages 15;00 to 19;11. The result of this discrete age cohort analysis, with Bonferroni correction applied to account for multiple comparisons, is summarized in Table I and also presented graphically for each variable in the lower left panel of Figures 2 to 10. In this paper, imaging studies in age Cohorts I & II are referred to as prepubertal, Cohort III as pubertal and Cohort IV as postpubertal. Such age-based grouping reference roughly matches Fitch & Giedd's (1999) pubertal stage grouping (based on Tanner's (1962) standardized rating system of pubertal stages) of prepubertal or pre-pubescent stage (age less than 10.3 years old), peripubertal or intermediate stage (ages 10.3 to 14.7 years old), and postpubertal or fully mature stage (ages 14.7 to 25.1 years).

Next, this comparison window was applied progressively by advancing it in one month increments from birth to 168 months where at each month x , the two sample t-test was done on [x, x+60-1] with all comparisons having more than 40 subjects/observations. The mean differences between males versus females for each comparison window are presented graphically, for each variable, in the upper right panel of Figures 2 to 10; and the corresponding p-values as a function of age are plotted in the lower right hand panel in Figures 2 to 10. To assist in the interpretation of the somewhat noisy p-values, a smoothing spline with generalized cross-validation was applied for each variable to smooth the obtained p-value functions; and the threshold of significance was marked in the figures with a gray dashed line at the corrected value of 0.0002. The p-value of 0.0002 corresponds to the Bonferroni correction of significance 0.05 divided by the number of test procedures (or number of windows). Thus, sex differences are considered to be significant if the p-values are below the dashed gray threshold line (bottom right panel in Figures 2 to 10). Note that the larger the mean sex differences are (upper right panel in Figures 2 to 10), the smaller are the p-values (lower right panel in Figures 2 to 10).

III. RESULTS

Localized assessment of sex differences for the four discrete age Cohorts I to IV are summarized in Table 1, and also presented graphically for each variable in the lower left panel of Figures 2 to 10. Taking into account the Bonferroni correction, significant sex differences ($p<.05$) are evident for six of the nine variables in Cohort IV with males leading these differences i.e. males have larger mean values. Such findings supportive of postpubertal sexual dimorphism (Cohort IV) are expected and confirm previously documented sex differences in the literature for select vocal tract structures, such as vocal tract length and pharyngeal length, despite differences in how these select variables were measured (Fant, 1966;King, 1952;Fitch and Giedd, 1999;Lieberman and McCarthy, 1999;Vorperian et al. 2009). In Cohort III, significant sexual dimorphism is present for only one variable in the vertical plane (NPhL) with females leading this difference during puberty and also postpuberty. Furthermore, and of greatest interest from this discrete age group comparisons, are the significant sex differences in Cohort II ($p<.05$) for two variables in the horizontal plane – namely VT-H and VT-O. Such an outcome documenting that select VT structures have significant prepubertal sex differences in the horizontal plane is novel. Although Lieberman et al. (2001) did not identify prepubertal sex differences in the horizontal plane, they did report that the oropharyngeal width is slightly larger in males between the ages 1.75 and 4.75 years. This is addressed further in the following section on moving window analysis, and then again in the discussion. Interestingly, these latter novel results on prepubertal sex differences of VT variables in the horizontal plane support inferences and hypotheses from studies documenting acoustic differences (Vorperian and Kent, 2007). This is addressed further in the acoustic implication section of the discussion.

Finally, of importance are the overall findings – as summarized in Table I – that sex differences at specific age cohorts do not imply that those differences will persist during the course of development i.e. extent of sex differences varies during the course of development.

For additional explorations on the nature of sex differences, this localized assessment was carried out again using a moving comparison window which was progressively advanced in one month increments from birth to 168 months. Figures 2 to 10 present the results graphically for each variable (upper left panel), where the average male versus female differences are depicted in the upper right panel, and immediately below it – in the lower right panel – is the display of the p-values comparing those male versus female differences. The p-values (lower right panel) were fitted with a smoothing spline, and a dashed gray line depicting the corrected .05 level or threshold of significance. Figure 2 displays the outcome for the variable VTL, Figures 3 to 5 display the results of variables in the vertical plane (VT-V, PCL, and NPhL), and Figures 6 to 10 display the outcome of variables in the horizontal plane (VT-H, LTh, ACL, OPhW, and VT-O). The results, as displayed in the upper and lower right panel of Figures 2 to 10, are in line with findings from the discrete age cohorts analyses/comparisons, but also clarify the approximate ages at which sex differences are present. Furthermore, the figures also display the tendencies of vocal tract structures towards sexual dimorphism at particular age ranges that may not necessarily be statistically significant, but are emerging and evident nonetheless. So, although the p-values are somewhat small, they are slightly above the Bonferroni corrected threshold of significance.

To further elaborate on the results of the moving window comparison, the lower right panel of Figure 2 displays the finding on sexual dimorphism of VTL. Significant sex differences are present at about age 12 years where the p-values are at or below the corrected threshold of significance. This outcome is consistent with the discrete age cohorts comparison results described above. More importantly however, the findings support what has been documented in the literature (e.g. Fitch and Giedd, 1999;Lieberman and McCarthy, 1999) and confirm the validity of this approach. Similarly, Figures 3 to 5, displaying results of variables in the vertical plane (VT-V, PCL and NPhL), indicate that the outcomes are again in line with the discrete age cohorts comparison summarized in Table 1; and also specify that while significant sex differences in VT-V (Figure 3) is present after about age 13 years, the differences for the constituent variables (PCL and NPhL) are emerging earlier at about age eight years with differences being led by males for PCL (Figure 4), and by females for NPhL (Figure 5). As for variables in the horizontal plane (VT-H, LTh, ACL, OPhW and VT-O), the results– as displayed in Figures 6 to 10 – are again in line with the discrete group comparison highlighting prepubertal and postpubertal differences for VT-H (Figure 6) and VT-O (Figure 10) between the approximate ages three to seven years, and 13 to 14 years and up respectively. In addition, the findings reflect a brief tendency towards sexual dimorphism, albeit not significant, in the variable OPhW (Figure 9) between the approximate ages two to four years. This latter is a finding that is very similar to that reported by Lieberman et al (2001) who noted that the oropharyngeal portion of the VT-H is slightly larger in males between the ages 1.75 and 4.75 years.

What is striking about the overall findings on prepubertal, pubertal and postpubertal sexual dimorphism is that variables in the vertical plane display significant sexual dimorphism past approximately age eight with differences persisting to age of maturity, whereas structures in the horizontal plane display prepubertal sexual dimorphism somewhere between the ages three to about seven years with the differences either re-emerging after approximately age 12 e.g. VTL (Figure 2), VT-H (Figure 6), and VT-O (Figure 10), or dissolving and remaining absent e.g. OPhW (Figure 9). As noted above, the one variable that does not show any sexual dimorphism throughout the entire developmental age range is ACL (Figure 8).

While the two variables LTh (Figure 7) and VTL (Figure 2) do not display a steady period of sexual dimorphism before age 12 years, it is evident that they each undergo a prepubertal period where male versus female differences are evident though not statistically significant (e.g. LTh, Figure 7, around age four years), or evident differences that fluctuate and do not hold steady at the significance level (e.g. VTL, Figure 2, around ages three to nine years).

IV. DISCUSSION

A. Current anatomic findings

This study provides localized analysis assessing prepubertal, pubertal and postpubertal sexual dimorphism in VT length and its oral and pharyngeal portions. The nine variables used in this follow-up study are the same variables used in an initial study by Vorperian et al (2009) where the non-uniform growth of the VT was quantified in terms of growth trend, growth rate and growth type. In that initial study, Vorperian and colleagues documented significant global sex differences in eight of the nine variables (all variables except ACL). Based on that finding, and the presence of distinct differences in overall growth trend, growth type and growth rate between males and females for all variables, this follow-up study with localized analysis was undertaken.

Present findings, based on both types of analyses (discrete age cohorts and moving window comparisons), unveil unequivocal evidence for the presence of periods of significant sexual dimorphism of select VT structures during the prepubertal, pubertal and/or postpubertal phases of development. Most novel is the result of significant prepubertal sexual dimorphism of select VT variables in the horizontal plane first, followed by a period of significant differences of VT variables in the vertical plane (at about age eight years) that persist well into the pubertal and postpubertal periods. These results not only attest to the importance of using a limited age range to reveal sexual dimorphism across development, but also draw attention to the importance of examining segments within a variable. The finding that there is sexual dimorphism of NPhL length during the prepubertal to pubertal phases with females displaying larger values than males is an original result. Thus although VT-V is significantly larger in postpubertal males, its PCL and NPhL segments display differences in sexual dimorphism across development due to their differences in growth trend, growth rate and growth type (Vorperian et al. 2009).

An additional finding of interest regarding VT variables in the horizontal plane that undergo a period of marked prepubertal sexual dimorphism (namely VT-H and VT-O) is that during the pubertal phase those same variables once again display a re-emergence of sexual dimorphism that persist into the postpubertal period. Given the documented differences in growth trend, rate and type between males and females (Vorperian et al., 2009), the data driven or model free approach used in this study, with localized smaller age range male/female comparisons (five year window), was critical in unveiling the prepubertal and pubertal sexual dimorphism of VT structures that have been elusive to date. In other words, as hypothesized, assessment of developmental sex differences using a wide age range, such as the first decade of life, is not sensitive to detect/capture such differences given the documented growth rate differences between males and females (Vorperian et al. 2009). Specifically, comparison for sex differences that combines five year age range Cohort I and Cohort II into a single prepubertal group (i.e. first decade of life) can automatically discard or wash out critical sex differences that are present (c.f. Fitch and Giedd, 1999). While the analysis approach used with repeated t-tests has the inherent problem of alpha inflation, the stringent Bonferroni correction applied overcomes the concern of falsely claiming significant results (Type I error). In other words, the presence of significant differences between males and females based on both types of analyses, in view of the highly stringent

correction criteria applied, assures that those differences are real particularly for the noted prepubertal differences in the horizontal plane.

To summarize, current study results, based on both types of analyses, indicate that sex differences in the oral and pharyngeal portions of the VT display different but chronologically complementary sexual dimorphism. Findings show significant prepubertal sexual dimorphism in VT-Horizontal length and VT-Oral length (between the approximate ages three-to-seven years), followed by significant pubertal and postpubertal differences of segments in the vertical plane or pharyngeal region with males having the larger measurements for VT-V and PCL but not for NPhL. More important than the age-specific sexual dimorphism is the result that sex differences vary during the course of development. That is, the presence of sex differences at specific ages does not necessarily imply that those differences persist during the course of development. As noted above, such a conclusion underscores the importance of the analysis approach used when assessing for sexual dimorphism.

B. Acoustic implications

The anatomic findings discussed above provide, though only in part, a promising biologic basis for the documented prepubertal speech acoustic differences between males and females prior to age 12 where there does not appear to be significant vocal tract length differences (Fitch and Giedd, 1999; Lieberman et al., 2001); and also where there are no consistent sex differences in vocal fundamental frequency (Perry et al. 2001; Whiteside, 2001; Vorperian and Kent, 2007).

More specifically, present anatomic findings documenting developmental sexual dimorphism of select VT structures, provide support to an acoustic driven hypothesis based on Fant's simplified two-tube model (oral cavity/front tube length and pharyngeal cavity/back tube length). Fant (1975) suggested that pharyngeal cavity length is affiliated with the second format, and oral cavity length is affiliated with the third formant. Based on the acoustic observation that the F1-F3 developmental dispersion pattern is greater than the F1-F2 pattern particularly in males (Vorperian and Kent, 2007), this study was undertaken with the hypothesis that there are sexually dimorphic differences in oral cavity length between male and female children. Indeed, this study is the first to document significant prepubertal sexual dimorphism of select VT structures in the oral region. Thus, despite the simplicity of Fant's two-tube model, and the fact that it ignores cross modes in the transfer function of the VT, it does provide a good first approximation and was instrumental in guiding this anatomic study.

Given the anatomic focus of this paper using static, at rest length measurements, it is premature to discuss anatomic-acoustic correlates beyond what is discussed above. However, present findings along with a number of acoustic observations, such as a decrease in formant frequencies in the aging population (Benjamen, 1997; Enders et al. 1971; and Linville & Fisher, 1985), point to the need to have detailed anatomic data of the oral and pharyngeal region across the entire lifespan. Specifically, it is necessary to secure cross sectional area and three-dimensional (3D) data that are developmental and sex specific to carefully examine anatomic-acoustic relationships (c.f. Sulter et al., 1992). Indeed, Fant (1966, 1975) called for more detailed anatomic studies, including laryngeal cavity dimensions, for the data to be used in establishing scaling factors for normalization which has been a long standing issue in speech science. Using acoustic pharyngometry, Xue and colleagues have reported sex differences in vocal tract dimensions for the elderly (Xue & Hoa (2003) and on adolescents (Xue, Cheng & Ng, 2010). These results provide some insight on developmental changes in the size (both length and volume) of the oral and pharyngeal portions of the vocal tract. Other acoustic observations that underscore Fant's

(1966) call for detailed anatomic studies include reports that formant frequencies remain unchanged (do not decrease) during the first two years of life despite increases in VTL (Buhr, 1980; Gilbert et al., 1997; Kent and Murray, 1982; Robb et al., 1997). Also, the report by Bloom, Moore-Schoenmakers, and Masataka (1999) on sex differences in the nasality of early vocalizations with boys' voices being less nasal than females calls for three-dimensional assessment of the naso-oro-pharygneal region. Similarly, an acoustic observation, summarized in Vorperian and Kent (2007), that by age seven or eight years males have consistently lower formant frequencies than females across all vowels despite the absence of significant sex differences in VTL calls for detailed anatomic assessment (cross-sectional and 3D) of the larygo-pharyngeal region particularly in light of the present anatomic finding on PCL where males have significantly longer PCL than females after age eight. Furthermore, the findings reported by Vorperian and Kent (2007) depicting notable jumps or skips in the F1-F2 and F1-F3 vowel acoustic space at certain ages with specific differences between males and females – where male acoustic data display an overall jump in F1-F2 and F1-F3 vowel acoustic space, whereas female acoustic data display a limited jump in the low vowel acoustic space – calls for detailed anatomic assessment of the oro-naso-larygopharyngeal region. This latter assessment need is based on the principle fact that low vowels require increased constriction of the pharyngeal region. Since both F1-F2 and F1-F3 vowel acoustic space display this distinct pattern of acoustic space jump – overall jump in males versus limited jump in the low vowel region in females (Vorperian and Kent, 2007; Figures 2, 3, 5 and 6) – and given present findings depicting a trend towards sexual dimorphism in the OPhW (Figure 9) first, followed by sexual dimorphism in both PCL (Figure 4) and NPhL (Figure 5) in opposite directions, it is reasonable to hypothesize that the combined effect of OPhW with PCL and NPhL accounts for the distinct sex-specific differences of jumps in acoustic space. As noted above, Lieberman et al. (2001) have reported oropharyngeal width (the distance from the posterior pharyngeal wall to the posterior margin of oral cavity) to be slightly larger in males between the ages of 1.75 and 4.75 years. Also, Vorperian et al. (2009) reported large differences in the growth type for the OPhW with males following a predominantly neural growth curve (61 % neural, 39% somatic), and females a predominantly somatic growth curve (75% somatic, 25% neural). Thus, various anatomic results combined with various acoustic observations are pointing to prepubertal developmental sex specific differences in the oro-naso-laryngopharyngeal region that warrants future research effort to provide sex-specific detailed anatomic quantification of developmental changes in this region.

Such detailed anatomic information characterizing the sex-specific non-uniform growth of the vocal tract is necessary to empirically advance our understanding of formant-cavity affiliations, and in particular determining developmental and also sex-specific anatomic changes that yield acoustic differences. In other words, the task is to determine the anatomic correlates for the noted developmental sex-specific changes/differences in speech acoustics. This may be accomplished by using the detailed anatomic parameters in vocal tract models (Story, 2005a, 2005b, 2009) or developmental articulatory models (e.g. Maeda, 1979, 1990 and Menard, Schwartz, and Boe, 2004), to help advance our understanding of exchanges and interplay of formant-cavity affiliations. Instances of transposition of formant frequencies have been reported during the course of development. For example, Martland, Whiteside, Beet, and Baghai-Ravary (1996) reported transposition of the F2 and F3 parameters due to growth differences of the pharyngeal and oral cavities, such that for children younger than 2 years, F3 is related primarily to the pharyngeal cavity i.e. formant-cavity affiliations that are opposite to the relationship established by Fant (1960).

To summarize, this is the first study that documents prepubertal, pubertal and postpubertal anatomic differences in the oral and pharyngeal portions of the VT. Although such anatomic sex differences could account for some of the documented acoustic sex differences during

the course of development, both the anatomic and acoustic findings to date point to an apparent need for detailed sex-specific quantification of the anatomic changes in the oro-naso-larygo-pharyngeal region during the entire course of development. Such information would be useful in articulatory or vocal tract modeling efforts to systematically examine sex-specific anatomic-acoustic correlates in terms of assessing required changes in anatomic measurements for the observed acoustic differences.

V. CONCLUSION

Assessment of sexual dimorphism using a small age range comparison window is more sensitive than global comparisons since potential sex differences can be masked by growth rate differences. The present study confirmed the presence of significant prepubertal sexual dimorphism in VT-Oral length in the horizontal plane between the ages 3-to-7 years, followed by significant sex-specific differences of segments in the vertical plane. Findings substantiate an anatomic basis of documented prepubertal speech acoustic differences. However, it is necessary to empirically validate anatomic-acoustic correlates via vocal tract modeling efforts based on accurate anatomic information.

Acknowledgments

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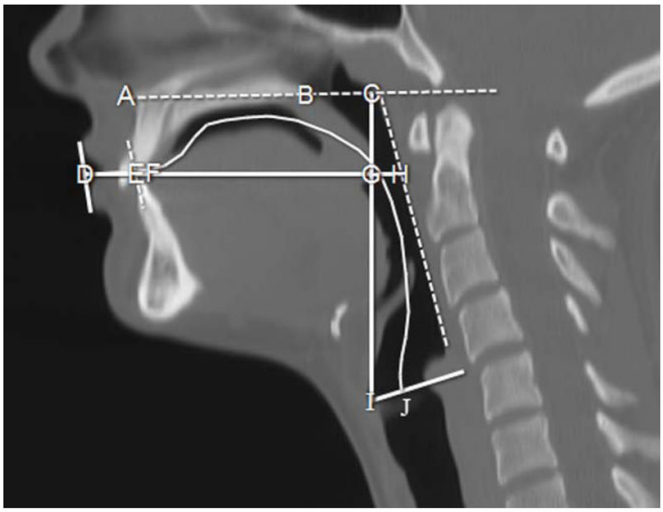

Figure 1.
Midsagittal CT image displaying the anatomic landmarks used for making measurements. The nine variable studied include: (1) *Vocal Tract Length (VTL)*, the curvilinear line extending from points D to J. (2) *Vocal Tract-Vertical (VT-V)* vertical distance from points I to C and consisting of two segments (3) *Posterior Cavity Length (PCL*; points I to G) and (4) *Nasopharyngeal Length (NPhL*; points G to C). (5) *Vocal Tract-Horizontal (VT-H)* horizontal distance from points D to H, consisting of three line segments: (6) *Lip Thickness (LTh*; points D toE), (7) *Anterior cavity length (ACL*; points F to G), and (8) *Oropharyngeal width* (OPhW; points G toH). Also, the segment (9) *Vocal Tract Oral* (VT-O; points E to H). By Vorperian et al., 2009, Journal of the Acoustical Society of America, 125(3). Copyright by the Journal of the Acoustical Society of America.

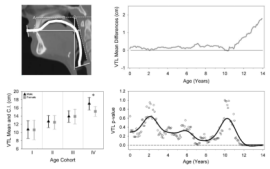

Figure 2.

Upper Left panel: Midsagittal CT image displaying the variable Vocal Tract Length (VTL). VTL is defined as the curvilinear distance along the midline of the vocal tract starting at the level of the glottis to the intersection with a line drawn tangentially to the lips.

Lower Left panel: Comparison of VTL means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Cohort I includes ages birth to 4;11 (4 years 11 months); Cohort II includes ages 5;00 to 9;11; Cohort III includes ages 10;00 to 14;11; and Cohort IV includes ages 15;00 to 19;11. Asterisk denotes the age cohort(s) with significant differences between males and females ($p<.05$). Numeric values are listed in Table I.

Upper Right panel: Mean differences in VTL between males and females at different ages. The thin black line at the zero level depicts level of no mean differences.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable VTL as a function of age. The individual p-values were fit with a smoothing spline to help visualize sex differences pattern. The dashed gray line depicts the corrected .05 level or threshold of significance. Values below the hashed gray line reflect significant sex differences.

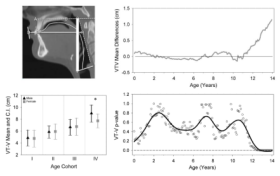

Figure 3.

Upper Left panel: Midsagittal CT image displaying the variable Vocal Tract-Vertical (VT-V). VT-V is defined as the vertical distance from the glottis to the palatal plane.

Lower Left panel: Comparison of VT-V means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in VT-V between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable VT-V as a function of age. Data plotted as described in Figure 2 caption.

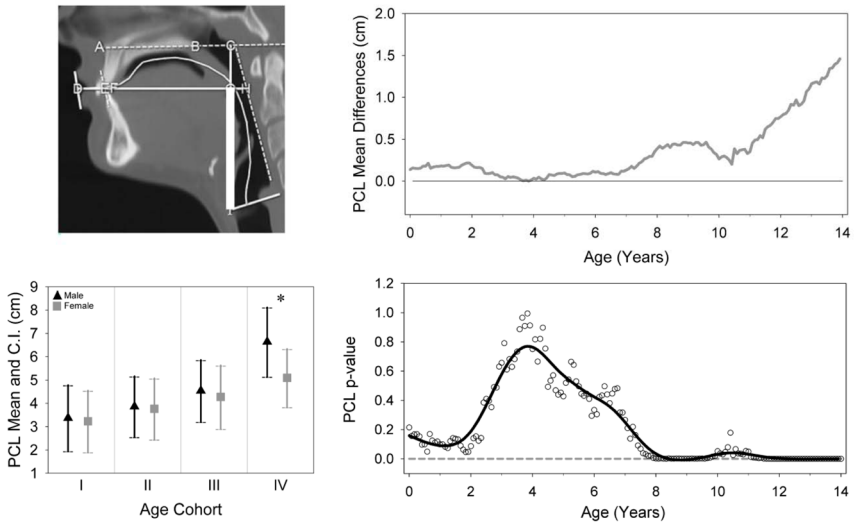

Figure 4.

Left panel: Midsagittal CT image displaying the variable Posterior Cavity Length (PCL). PCL is defined as the vertical distance of a line drawn from the glottis to the intersection with the end of the oral or anterior cavity length.

Lower Left panel: Comparison of PCL means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in PCL between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable PCL as a function of age. Data plotted as described in Figure 2 caption.

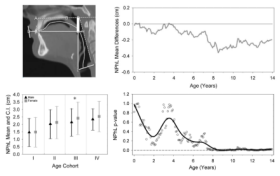

Figure 5.

Left panel: Midsagittal CT image displaying the variable Nasopharyngeal length (NPhL). NPhL is a calculated measurement of VT-V minus PCL.

Lower Left panel: Comparison of NPhL means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in NPhL between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable NPhL as a function of age. Data plotted as described in Figure 2 caption.

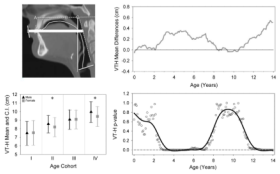

Figure 6.

Left panel: Midsagittal CT image displaying the variable Vocal Tract-Horizontal (VT-H). VT-H is defined as the horizontal distance from a line tangential to lips to the posterior pharyngeal wall.

Lower Left panel: Comparison of VT-H means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in VT-H between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable VT-H as a function of age. Data plotted as described in Figure 2 caption.

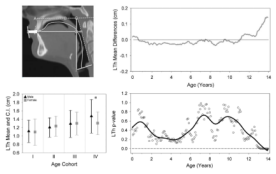

Figure 7.

Left panel: Midsagittal CT image displaying the variable Lip Thickness (LTh). Lip Thickness defined as the distance between two lines, the first of which is drawn tangential to the anterior aspect of the maxillary and mandibular lips, and the second to the posterior or buccal aspect of the maxillary and mandibular lips.

Lower Left panel: Comparison of LTh means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in LTh between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable LTh as a function of age. Data plotted as described in Figure 2 caption.

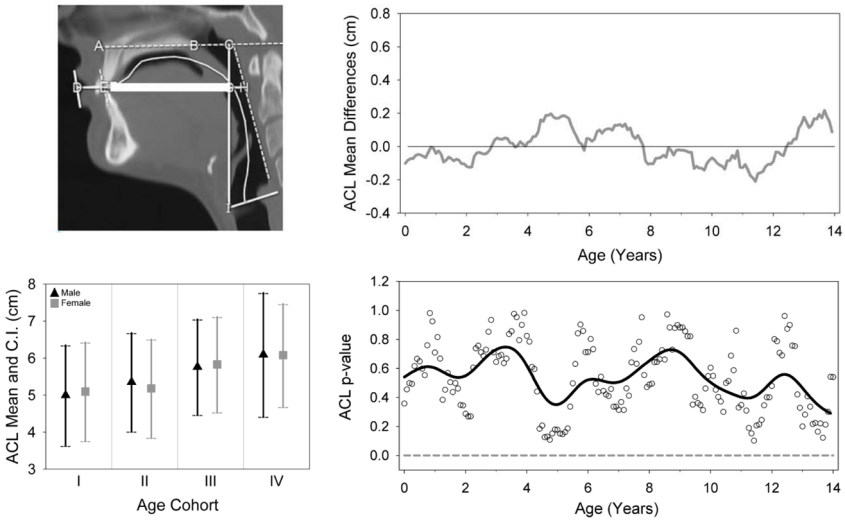

Figure 8.

Left panel: Midsagittal CT image displaying the variable anterior cavity length (ACL). ACL is defined as the horizontal distance from the beginning of the hard palate to the intersection with the vertical line drawn from the glottis to the palatal plane.

Lower Left panel: Comparison of ACL means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in ACL between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable ACL as a function of age. Data plotted as described in Figure 2 caption.

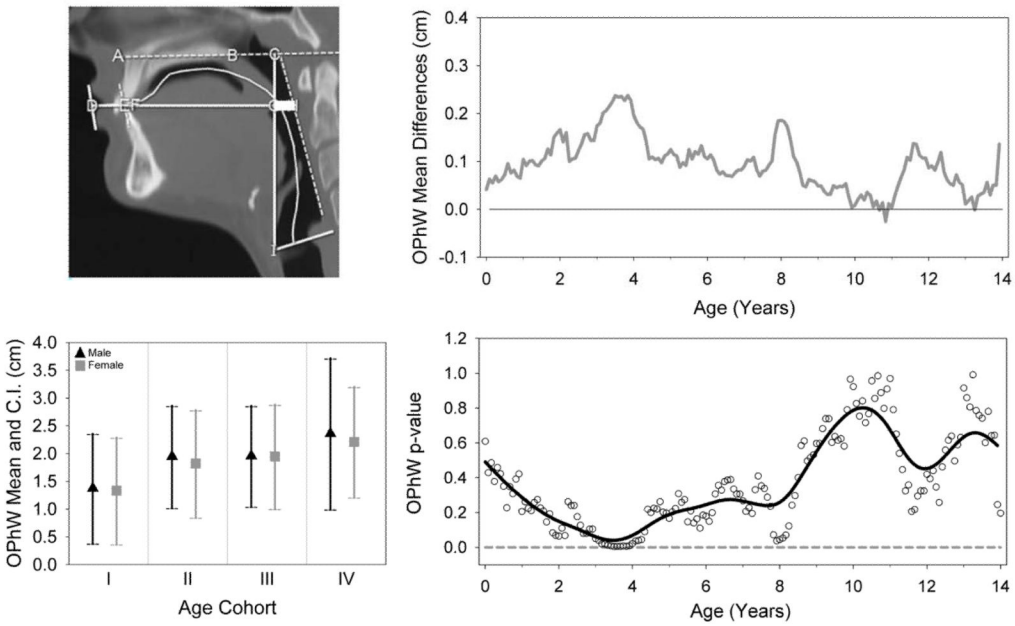

Figure 9.

Left panel: Midsagittal CT image displaying the variable Oropharyngeal Width (OPhW). OPhW is calculated using the measurements of VT-H minus LTh minus ACL.

Lower Left panel: Comparison of OPhW means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in OPhW between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable OPhW as a function of age. Data plotted as described in Figure 2 caption.

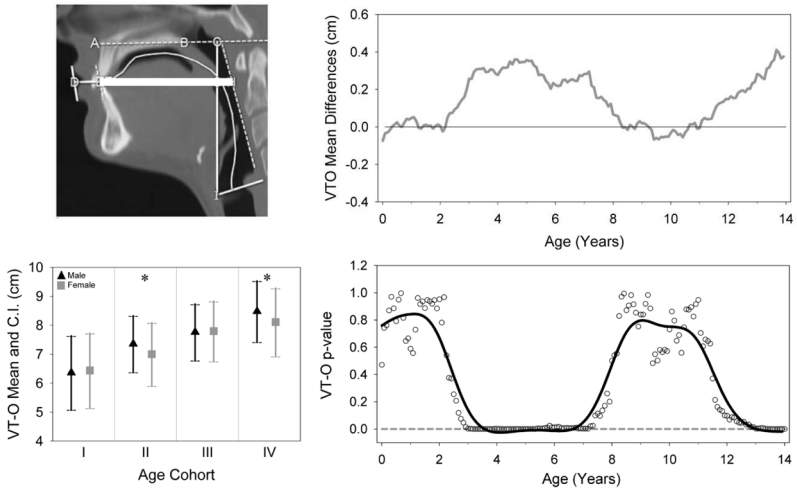

Figure 10.

Left panel: Midsagittal CT image displaying the variable Vocal Tract-Oral (VT-O). VT-O is calculated using the measurements VT-H minus LTh.

Lower Left panel: Comparison of VT-O means and confidence intervals (C.I.) between males (black triangle) and females (gray square) for the four discrete age cohorts (I-IV). Data plotted and reported as described in Figure 2 caption.

Upper Right panel: Mean differences in VT-O between males and females at different ages. Data plotted as described in Figure 2 caption.

Lower Right panel: Plot of p-values comparing male versus female differences using the 60 month moving window for the variable VT-O as a function of age. Data plotted as described in Figure 2 caption.

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Table I

Summary t-test results for gender effect comparing the discrete age cohorts I to IV for the nine variables studied. Cohort I includes ages birth to 4;11 (4 years 11 months); Cohort II includes ages 5;00 to 9;11; Cohort III includes ages 10;00 to 14;11; and Cohort IV includes ages 15;00 to 19;11. For each variable and each age cohort, the number of measurements available and included in the analysis, number of outliers, mean, and standard error of the mean (S.E.M.) is specified for males and females. The last two columns list the p value and specify significance with Bonferroni correction.

Variable	Age Cohort	Males			Female			T-stat	df	P- value	BonferroniSignif. N/Y
		n/ Outliers	Mean	S.E.M.	n/ Outliers	Mean	S.E.M				
VTL	I	98/1	10.74	0.151	64	10.65	0.111	−0.47	125	0.6426	N
	II	78	12.69	0.124	47/1	12.49	0.085	−1.36	87	0.1760	N
	III	50	13.92	0.129	51	13.92	0.103	0.00	94	1.0000	N
	IV	44/3	17.04	0.083	53/2	15.14	0.118	−13.15	80	0.0000	Y
VT-V	I	97/1	4.86	0.091	64	4.76	0.070	−0.83	129	0.4079	N
	II	78	5.87	0.093	50	5.93	0.060	0.54	88	0.5877	N
	III	53	6.66	0.103	52/6	6.76	0.094	0.71	101	0.4776	N
	IV	44/4	8.98	0.079	58	7.73	0.111	−9.16	81	0.0000	Y
PCL	I	98/1	3.37	0.084	65	3.23	0.073	−1.25	143	0.2149	N
	II	78	3.86	0.096	49	3.77	0.076	−0.80	101	0.4278	N
	III	53	4.54	0.098	51	4.28	0.093	−1.96	101	0.0527	N
	IV	45	6.64	0.087	54	5.09	0.113	−10.82	86	0.0000	Y
NPhL	I	97/9	1.47	0.064	63/8	1.49	0.049	0.23	127	0.8211	N
	II	77/7	2.02	0.079	50	2.13	0.057	1.11	96	0.2680	N
	III	52/5	2.14	0.076	53/2	2.42	0.065	2.72	100	0.0076	Y
	IV	48/5	2.35	0.071	54/9	2.54	0.053	2.15	95	0.0341	N
VT-H	I	99/2	7.48	0.085	74	7.53	0.072	0.46	155	0.6459	N
	II	93	8.55	0.076	56	8.20	0.054	−3.72	107	0.0003	Y
	III	67	9.08	0.069	66	9.10	0.071	0.17	130	0.8665	N
	IV	53/2	9.96	0.074	64/1	9.44	0.086	−4.65	108	0.0000	Y
LTh	I	101	1.12	0.019	71/1	1.10	0.014	−0.80	134	0.4233	N
	II	85	1.21	0.016	56	1.24	0.013	1.47	115	0.1456	N
	III	66	1.29	0.016	75	1.30	0.020	0.41	128	0.6810	N

Variable	Age Cohort	Males			Female			T-stat	df	P- value	BonferroniSignif. N/Y
		n/ Outliers	Mean	S.E.M.	n/ Outliers	Mean	S.E.M				
	IV	51/4	1.47	0.017	66	1.31	0.029	−4.95	83	0.0000	Y
ACL	I	99	5.00	0.085	65	5.10	0.070	0.92	138	0.3580	N
	II	75	5.35	0.098	48	5.18	0.079	−1.36	100	0.1768	N
	III	52	5.76	0.092	52	5.83	0.092	0.52	101	0.6047	N
	IV	46/2	6.10	0.095	56	6.08	0.126	−0.09	87	0.9246	N
OPhW	I	94/5	1.37	0.062	64/1	1.33	0.052	−0.51	138	0.6087	N
	II	74/1	1.94	0.071	49	1.82	0.055	−1.39	99	0.1670	N
	III	49/1	1.95	0.066	53	1.95	0.066	−0.10	99	0.9234	N
	IV	45/3	2.36	0.070	53/3	2.21	0.104	−1.20	79	0.2324	N
VT-O	I	98/3	6.36	0.078	72	6.44	0.066	0.72	151	0.4710	N
	II	89	7.36	0.074	57	7.00	0.053	−3.92	109	0.0002	Y
	III	64	7.77	0.065	66/2	7.80	0.062	0.34	127	0.7315	N
	IV	53/2	8.48	0.075	65/1	8.11	0.074	−3.53	114	0.0006	Y