ISSN 1799-2591
Theory and Practice in Language Studies, Vol. 14, No. 4, pp. 931-940, April 2024
DOI: https://doi.org/10.17507/tpls.1404.01

A Cross-Language Comparative Study of English and German Vowel Space Area in Swiss German L1 Speakers

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***Abstract*—It is conventional to examine vowel systems by their acoustic correlates, specifically formants. In the International Phonetic Alphabet (IPA) vowel chart, vowels are placed according to their relative positions determined by the first two formant values. This two-dimensional plane makes possible the calculation of the articulatory working space of vowels. Variations in the size and shape of the vowel space exist across gender, dialects, and languages. The present study focuses on comparing the vowel space area (VSA) in English and German produced by native Swiss German speakers, attempting to shed light on whether VSAs differ significantly with different calculation methods cross-linguistically. Given the fact that absolute formant values vary tremendously across gender, Hertz values are converted to z-scores, allowing for more direct and meaningful comparisons. While vowel normalization mitigates gender-related differences within specific languages to a large extent, there remains a significant cross-linguistic gender difference. The results reveal that for 3- and 4-vowel space there is no significant effect in language but an effect is observed in gender and vowel combination on VSA, specifically in terms of individual area and overlapping ratio. This suggests that Swiss German speakers tend to utilize the same amount of vowel space in both languages, with the only difference being the expansion of English VSA in higher F2 dimension and lower F1 dimension, as observed across all calculation methods.**

***Index Terms*—vowel space area, phonetic variation, vowel normalization, cross-language comparison**

I. Introduction

The source-filter model (Fant, 1960) states that the speech sounds are produced when the source signal emanating from the vocal folds is modified by the vocal tract as a filter. The resulting resonance peaks favored by the filter configurations are formants, characterizing the vowels together with their duration. In acoustic study focusing on vowel quality, representing vowels by the first (F1) and the second formant frequency (F2) has long been a tradition. F1 and F2 correspond to the resulting resonance peaks in oral and pharyngeal cavities, respectively. “Vowel height is inversely proportional to the value of F1, and vowel advancement is directly proportional to F2 value” (Thomas, 2017, p. 145). The vowels are positioned accordingly in the acoustic dimension. The idealized shape is vowel quadrilateral, formed by connecting the cardinal vowels on the periphery, as specified in the IPA. However, the actual vowel chart for different languages may vary considerably due to the size and constituents of their peculiar vowel inventories. The question arises as to how the vowel space area changes with respect to the different number of cardinal vowels involved. The triangular area defined by three corner vowels /i: a: u:/ has been utilized in a number of research (Fox & Jacewicz, 2017), but it severely underestimates the actual working space due to the limited inclusion of vowels encompassed in computing the area. Therefore, the present study intends to explore different VSA computing methods for two languages with distinct vowel inventories, aiming to provide insights into the variation of VSA within and across languages.

VSA is a widely used metric in diverse research fields, as it is considered a common indicator of speech development. Pettinato et al. (2016) examined the vowel space area in later childhood and found that children's VSA were significantly larger than the adults', which is in accordance with the previous findings of age-related reduction in VSA (Flipsen & Lee, 2012). Moreover, there is evidence that the expansion and compression of VSA are relevant to speech intelligibility, in that people tend to expand their vowel space for the speech to be more acoustically distinct under challenging environments. In pathology, VSA acts as the description and evaluation of vowel articulation in such disorders as Parkinson’s disease, Down syndrome and dysphonia (Skodda et al., 2011; Bunton & Leddy, 2011; Roy et al., 2009). More intuitively, VSA is also closely related to speech style, where expanded area is observed in clear speech and reduced area in casual speech. Another pervasive application of VSA can be found in cross-dialectal comparison. Jacewicz et al. (2007) investigated whether the significant variation in vowel systems among three regional varieties of American English also affects the size of their respective dialect-specific vowel spaces.

The various utilities of VSA prove this quantitative index to be applicable in quite a few circumstances. As mentioned, VSA as an acoustic metric is mainly applied to regional dialect variations in previous research to study vowel shift in dialect varieties. Some efforts were made to L2 acquisition, as in the study investigating the impact of L1 interference on the vowel space area in Javanese and Sundanese English language learners (Perwitasari et al., 2016). However, cross-language comparison of VSA hasn't been given as much attention. Jongman et al. (1989) conducted a study on the acoustic vowel space of Modern Greek and German. The effect of the number of vowel inventory of two Arabic dialects, Moroccan and Jordanian Arabic, and French on the size of its vowel space was studied by Al-Tamimi and Ferragne (2005). They found that the larger the vowel inventory, the bigger the acoustic vowel space. However, only the triangular area was calculated in this cross-linguistic comparison. The similar hypothesis was also examined in a comparative study in relation to English and Spanish vowels (Bradlow, 1995), which proposed that the acoustic vowel space of English with higher density of vowel inventory may be expanded with respect to less dense acoustic vowel space of Spanish. On the other hand, extensive research has been conducted on vocalic variation among various Swiss German dialects. However, there is limited knowledge regarding the vocalic variation between German and English articulated by native Swiss German speakers. The present study is an attempt to investigate the variations in the size and dimension of the VSA as a function of computational methods, languages, and speaker gender.

It is hypothesized that the size and shape of vowel space area between German and English in Swiss German L1 speakers differ in the same calculation methods, the variation of vowel space area within German or English differ across different calculation methods, and gender plays a significant role in the space area variability. To examine these hypotheses, statistical testing as ANOVA and interaction analysis will be employed as primary approaches for data analysis.

II. Methods

A. Speakers

The participants of the study were 6 native Swiss German speakers (3 male and 3 female) who came from Winterthur, Switzerland. The speakers were aged between 25 and 35 (mean age: 33 years, SD: 2.1 years), and all of them were born and raised in the canton of Zurich. A proficient understanding of English and German was a prerequisite for participating in this production experiment, thus requiring participants to possess a comparable educational background, preferably at a college-level or higher, in both languages. None of the participants reported any hearing impairment or speech disorder. An informed consent form of the study was signed by each participant.

B. Materials and Procedure

The survey primarily concentrates on read speech rather than spontaneous speech. While spontaneous speech allows for more natural production, acquiring an adequate number of tokens for less common vowels poses a challenge. The entire vowel inventory is necessary for later vowel normalization and VSA computation. Read speech facilitates the controls on variables, enabling utterances to be directly comparable across different speakers (Thomas, 2017, p. 253). The German sentence list (see Appendix A) containing all the vowels of interest was constructed on the basis of a prior study (Simpson, 1997, pp. 273-276). The English sentence list (see Appendix B) was created through reference to the Oxford dictionary of English (Stevenson, 2010). There are 16 German vowels and 12 English vowels under study. Diphthongs have been excluded from this study due to their complexity. The vowel inventories being examined consist solely of monophthongs. To mitigate the influence of pitch variation, narrative statements are preferred. The length of the sentences, composed of high-frequency words, is limited to a maximum of 15 words, in order to ensure a realistic representation of daily speech patterns. There are no constraints on the occurrence of target vowels within the embedded words, meaning that the study considers all the contexts, including vowels next to an approximant or a nasal. It is recommended that each vowel should have a minimum of 20 tokens when the speakers' entire vowel inventories are mapped (Thomas, 2017, p. 159). The study adequately fulfills this requirement, as there are a large number of tokens for each vowel. Additionally, the vowel space area should encompass a wide range of contexts, in that it represents the potential maximal articulatory space.

All recordings were made in a quiet room in Winterthur. Prior to the recording session, the speakers were provided with the sentence lists to familiarize themselves with the materials. They were instructed to read each set of sentences in both languages with normal speed and natural accent. The speakers were seated in front of the computer screen and speaking into a USB-cabled external recorder (USBPre2 G604). The sampling rate was set to 44.1 kHz in Praat SoundRecorder interface (Boersma, 2011). A headset microphone (VT800H) was connected to the recorder and positioned approximately 5 centimeters at the side of the speakers' lips. A total of 594 sentences were recorded from all speakers, with one speaker unable to complete the remaining 12 German sentences due to personal reasons. For ease of description, male speakers are labeled as M and female speakers as F. The speakers are numbered for subsequent reference. All the recordings were saved in WAV format and named according to the respective speaker's ID code.

The sound files were truncated to facilitate easier processing, and subsequently annotated in SAMPA to ensure compatibility with the Praat script and normalization software, thereby avoiding erroneous outcomes. It is important to note that the equal numbers of recorded sentences do not necessarily indicate the same quantities of selected tokens for each speaker. Certain tokens were disregarded or excluded due to factors such as incorrect pronunciation, weak formant tracking in the spectrogram, and the like. The onset and offset of vowels in various contexts were consistently annotated. The script trimmed 20% of the duration from both the onset and offset, retaining only the central 60% of the interval.

Median values were then measured and extracted for each individual token. The empirical data included 1972 German vowel tokens and 1799 English vowel tokens in total.

C. Vowel Normalization Methods

Anatomical differences, such as thicker vocal folds and the longer vocal tract in males, contribute to lower fundamental frequency and formant values. It has been proved to be effective to normalize the physiological differences within the same language variety in a meaningful linguistic way. In this study, the primary focus is on the comprehensive examination of the entire vowel inventory in each language. Therefore, vowel-extrinsic methods are preferred as information across multiple vowel realizations are used to normalize one specific vowel. A comparative study by Flynn (2011) demonstrated that vowel-extrinsic, formant-intrinsic, and speaker-intrinsic methods outperform other methods at normalizing speakers' vowel spaces. This study employed Lobanov's method, first introduced by Lobanov (1971) and commonly known as the z-score method. It works optimally when all the vowels of a speaker's vowel system are included in the procedures. The formula of z-score transformation is shown as in Eq. (1).

$$F_i^N = (F_i - M_i) / \sigma_i, \quad (1)$$

where F_i^N denotes the normalized value for F_i, the formant i of the vowel. M_i is the mean value of formant i across all the included vowels for the speaker and σ_i refers to the standard deviation for the mean M_i. The normalizing procedures were completed by the vowel normalization and plotting suite NORM (Thomas & Kendall, 2017).

D. Vowel Space Area Computations

The vowel space areas for each language and gender were calculated using normalized z-scores in the R software. The calculation of the VSA was primarily based on combination of common vowels and vowel dispersion theory. The dispersion theory (Lindblom, 1986) proposes that vowels tend to be distributed in the acoustic space so as to maximize the perceptual distinctiveness to contrast separate vowel categories. VSA was defined by a set of cardinal vowels in the corner and peripheral positions. The mean values of F1 and F2 of the involved vowels were used as reference points to locate the extent of the area. The primary focus of the current study is on the convex hulls of the vowel space areas in each gender, including triangular, quadrilateral, and multilateral shapes. Concave hulls were not considered due to the adoption of dispersion theory. Both German and English have large vowel inventory according to Maddieson (2013), with overlapping in vowel categories, among which are /iː/, /uː/, /ɔː/, /aː/, and /ɛ/. The extent, shape and dimension in the VSA were compared. The individual vowel space area, the total area and intersection area were calculated.

III. Results

A. Vowel Normalization

Although English vowel inventory consists of two additional vowels compared to German, the vowel distribution of English is more dispersed, while German vowels tend to occupy a more concentrated acoustic space. This suggests that English vowels have distinct individual acoustic characteristics, whereas German vowels share a common acoustic space to a greater extent. The increased variability observed in English vowels may be attributed to the non-nativeness of the speakers. The anatomical differences were minimized with z-scores, for there is more overlapping of the ellipses clouds as depicted in Fig. 1.

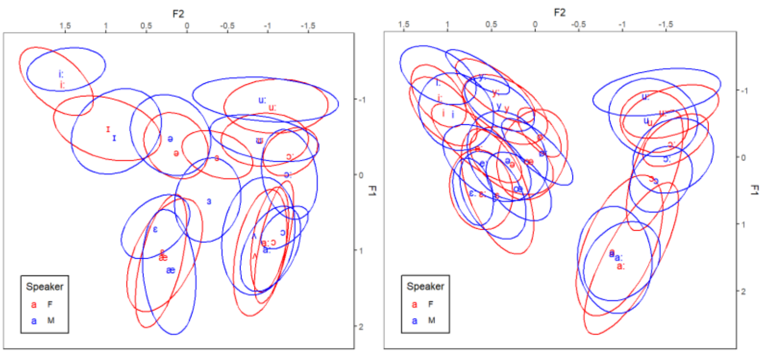

Figure 1. Normalized English (Left) and German (Right) Vowel Ellipses

Nevertheless, as demonstrated in the point plots in Fig. 2, notable differences in specific vowel categories persist, thereby enabling cross-language comparisons with regards to gender-related differences.

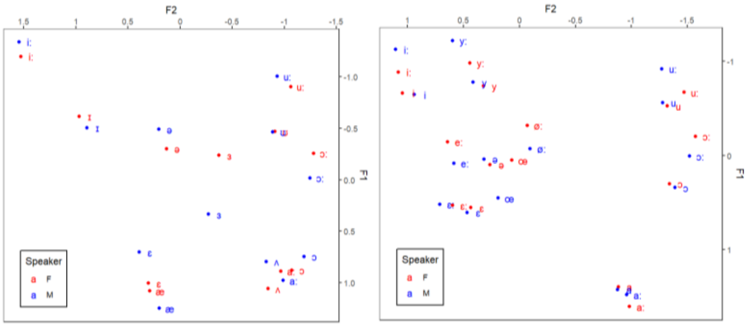

Figure 2. Normalized English (Left) and German (Right) Vowel Points

B. Triangular Vowel Space

The 3-vowel space area is characterized by three corner or peripheral vowels, representing the smallest possible vowel space. The traditional 3-vowel space consists of /a:/, /i:/, and /u:/, which are considered the most distinct vowels in terms of both acoustic properties and perceptual characteristics. Fig. 3 depicts the visualization of the triangular area /a: i: u:/.

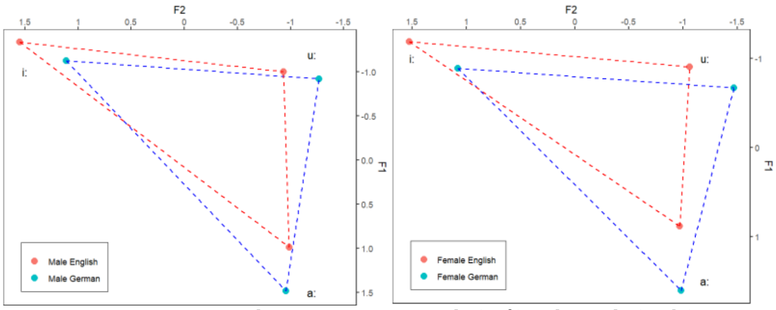

Figure 3. Triangular VSA /a: i: u:/ in Male (Left) and Female (Right)

The VSA sizes for the same language are similar for both genders. One of the reasons may be that similar vowel categories across two languages may differ in a systematic way due to a consistent language-specific adjustment of the articulators (Bradlow, 1995). However, the shapes of genders across language and the overlapping of languages across gender differ. Male speakers exhibit a higher degree of overlapping when producing different languages, suggesting that males may utilize a larger common acoustic space compared to females for these three vowels. Meanwhile, there is a noticeable variation in the trajectory of the vowels /a:/ and /u:/ in English. In this case, male speakers show a negative slope, whereas female speakers show a positive slope. In the English context, the F2 for /u:/ is higher for males than for females. In the German context, all slopes exhibit positive values, but the rate is greater among males. It can be concluded that /u:/ has extended in F2 dimension in both language contexts for male speakers.

This study intends to explore the VSAs for different combinations of five common vowels as a function of gender and language, as well as the relationship between overlapping VSAs and individual VSAs. A total of 10 combinations were analyzed, and the VSA data for each combination are presented in Table 1.

TABLE 1
VSAs OF 3-VOWEL COMBINATIONS IN EACH GENDER AND LANGUAGE

Combination		*/a:i:u:/*			*/i: u: ɔ:/*		
Gender	*Language*	*Individual*	*Total*	*Overlapping*	*Individual*	*Total*	*Overlapping*
F	*German*	2.961	3.521	1.771	0.586	1.053	0.340
	English	2.331			0.806		
M	*German*	2.890	3.223	2.125	1.079	1.420	0.826
	English	2.459			1.167		
Combination		*/i: u: ɛ/*			*/i: ɔ: a:/*		
F	*German*	1.770	2.872	1.559	2.603	2.819	1.536
	English	2.660			1.752		
M	*German*	1.999	2.566	1.771	2.257	2.352	1.472
	English	2.339			1.567		
Combination		*/i: ɔ: ɛ/*			*/i: a: ɛ/*		
F	*German*	1.692	2.566	1.630	0.684	1.581	0.566
	English	2.504			1.462		
M	*German*	1.917	2.266	1.742	0.954	1.480	0.720
	English	2.092			1.246		
Combination		*/u: ɔ: a:/*			*/u: ɔ: ɛ/*		
F	*German*	0.228	0.455	0.000	0.507	0.880	0.278
	English	0.227			0.651		
M	*German*	0.446	0.686	0.047	0.998	1.232	0.685
	English	0.286			0.920		
Combination		*/u: a: ɛ/*			*/ɔ: a: ɛ/*		
F	*German*	1.875	2.076	0.932	1.596	2.083	0.163
	English	1.133			0.651		
M	*German*	1.846	2.022	1.178	1.294	2.170	0.044
	English	1.355			0.920		

The VSA sizes between German and English vary to a greater extent for the combinations involving /ɛ/, largely resulting from the upward shift in F1 dimension for this particular vowel in German. As shown in Fig. 4, the combinations with /u:/ involved have great variabilities across gender, consistent with the observation that male speakers demonstrate an extended F2 dimension for /u:/ in both language contexts. An effect of combinations is observed in one-way ANOVA of combination on individual VSA [F(9,36) = 19.64, p < .001] and overlapping ratio [F(9,36) = 26.1, p < .001].

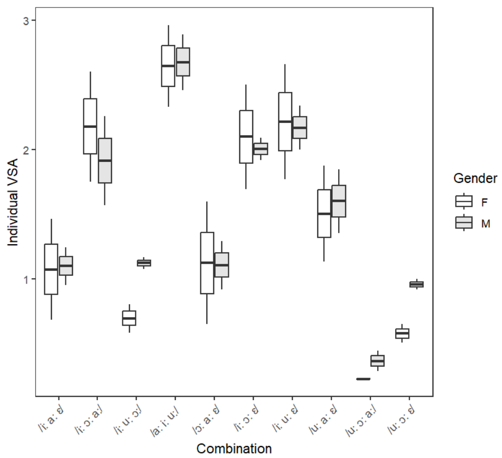

Figure 4. Distribution of Triangular VSA by Gender and Combination

In an ANOVA comparing individual VSA and overlapping ratio in all contexts, the main effect of individual VSA differences (F = 33.15, p <.001) reaches significance. As seen from Fig. 5, there is positive correlation between individual VSA and overlapping ratio, implying that the vowel categories with larger space tend to has increased intersection space across languages. There is no effect observed for languages on the variability of VSA, but the interaction analysis reveals that gender significantly influenced the VSA variability (F = 6.257, p < .05).

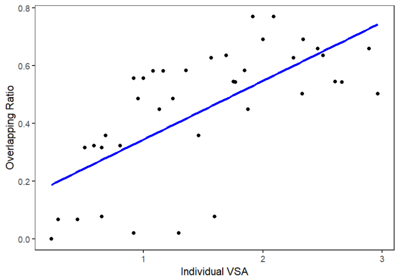

Figure 5. Relationship Between Individual VSA and Overlapping Ratio

C. Quadrilateral Vowel Space

Four corner or peripheral vowels establish the extended 4-vowel space area. The traditional cardinal vowels for research on English vowel space are /i:/, /æ/, /a:/, and /u:/. Given the emphasis on comparing vowel spaces formed by the common German and English vowels, the traditional method will not be utilized in the computation of the quadrilateral area. Fig. 6 depicts the VSAs in the five combinations with respect to language and gender. The formant trajectories in lower F1/F2 dimensions show greater consistency across gender and languages. However, in higher F1/F2 dimensions, the language-related differences are more evident, particularly in relation to females who demonstrate more variations.

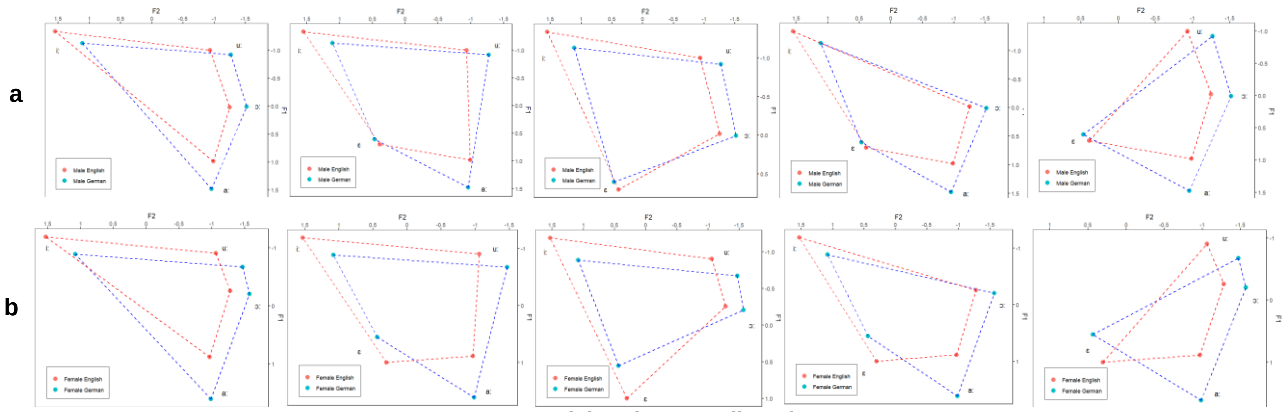

Figure 6. Quadrilateral VSA in All Combinations
(a) VSA in Male Speakers (b) VSA in Female Speakers

Similarly, the variability in VSAs varies significantly across different combinations, both in terms of individual areas [$F(4,15) = 15.77$, $p < .001$] and overlapping ratios [$F(4,15) = 3.786$, $p = 0.0254$]. The effect of gender on the variability of quadrilateral areas is statistically significant. Contrary to the 3-vowel space, Fig. 7 displays that the inclusion of /u:/ in the combinations exhibits less pronounced variation, which may imply that the additional vowel contributes to a compensable space.

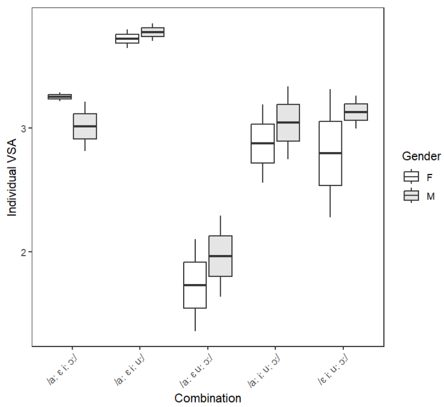

Figure 7. Distribution of Quadrilateral VSA by Gender and Combination

D. Multilateral Vowel Space

The study examines two multilateral vowel space areas, namely pentagonal area and hexagonal area. The pentagonal area is defined by five common vowel /a: ɛ i: u: ɔ:/, whereas the hexagonal area represents the maximum vowel space possible within a specific language. German hexagonal area is represented by /a: ɛ i: y: u: ɔ:/, while German hexagonal area is encompassed by /a: æ i: u: ɔ: ɔ/ for males and /ʌ æ i: u: ɔ: ɔ/ for females, in accordance with dispersion theory. From Fig. 8, the similar upward and leftward shift in quadrilateral area can also be observed here for English vowel spaces, indicating the expansion of English VSA in higher F2 dimension and lower F1 dimension. The low back vowels and low front vowels contribute to the discrepancy in the overall shape.

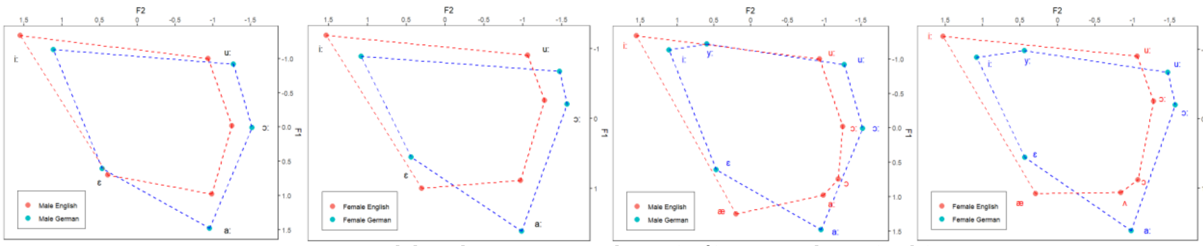

Figure 8. Multilateral VSA: Pentagonal Area (Left) Hexagonal Area (Right)

E. All Shapes of VSA

The results for the respective calculation methods illustrate the relationship among the individual VSA, the overlapping ratio and combinations. When all the methods considered together, there is significant effect of the VSA shape (same with the number of vowels involved) on individual VSA ($F = 40.9$, $p < .001$), as well as overlapping ratio ($F = 6.958$, $p < .001$).

In Fig. 9, the number of vowels involved in determining the vowel space is positively correlated to both individual area and overlapping ratio. Noticeably, the regression slope on the right is lower than that on the left, indicating that the relationship between shape and overlapping ratio is weaker compared to the relationship between shape and individual area.

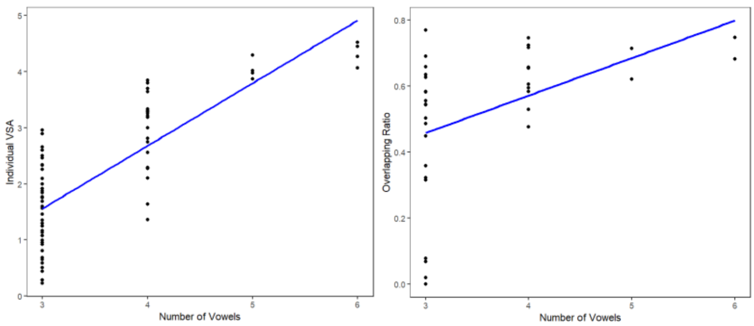

Figure 9. Relationship Between VSA Shape and Individual VSA (Left) and VSA Shape and Overlapping Ratio (Right)

On the other hand, as observed in Fig. 10, the rate and amount of the increase in VSA from triangular areas to quadrilateral areas is more prominent than multilateral ones. This finding suggests that the inclusion of more vowels results in a more complete VSA.

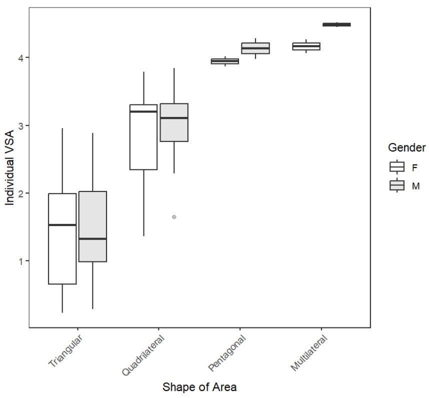

Figure 10. Individual VSA in Different Area Shapes

IV. Conclusion

The present study examines vowel space area in English and German produced by native Swiss German speakers. It compares the discrepancies in VSA based on factors such as language, gender, and calculation methods. The results show that the effect of language fails to reach significance in triangular and quadrilateral space. However, gender and vowel combination do influence VSA, particularly concerning individual area and overlapping ratio. These findings suggest that Swiss German speakers utilize a similar amount of vowel space in both English and German, but there are disparities in how the vowel space expands and compresses across the languages. Furthermore, there is a positive correlation between individual area and overlapping area. The more involved vowels, the larger the area.

The study contributes to understanding the variations in VSA within and across languages and sheds light on the impact of gender on vowel production. The findings highlight the importance of considering gender-related differences and calculation methods when comparing vowel space areas in various languages. Further research could explore the inclusion of concave hulls and conduct detailed investigations into the shape of VSA as potential topics for studying cross-language vowel space variation.

Appendix A English Sentence List

1. I love to cook eggs for breakfast.
2. The sun is shining bright today.
3. The cat sat on the table.
4. Turn off the light before you leave.
5. My brother loves to run, even when it's raining.
6. The music at the concert was amazing.
7. I need to water the plants before they die.
8. He always wears a suit and tie to work.
9. She is very excited to see the new movie.
10. The snowstorm lasted for three days.
11. The restaurant has a great selection of seafood.
12. He bought a new car with leather seats and a sunroof.
13. She teaches Spanish at the local high school.
14. My dad likes to watch football on Sundays.
15. She has a beautiful voice and sings with passion.
16. He found the missing book under the sofa.
17. The farmer planted rows of corn in his field.
18. The child was afraid of the loud thunderstorm.
19. She enjoys hiking in the mountains and taking in the view.
20. The tourist took many photos of the famous monument.
21. She jumped up and down in excitement.
22. I took a look at the book and put it back on the shelf.
23. The school rules state that all students must wear uniforms.
24. He sits in the same spot every day and reads his book.
25. We should go to the store before it closes.
26. My father works as a carpenter and builds furniture
27. She heard a bird chirping outside her window.
28. The boy played with his toy car on the floor.
29. I saw a mouse run out of the house.
30. She loves to run on the grass.
31. The dog barked loudly at the postman.
32. The box was full of old photographs.
33. The hotel room had a comfortable sofa for guests to relax on
34. The festival was so much fun.
35. The house down the road is for sale.
36. The earthworms burrow deep in the soil.
37. The boy enjoyed playing with his toy truck and making engine noises.
38. The artist painted a beautiful landscape with shades of purple and blue.
39. My best friend likes to drink peppermint tea for its refreshing taste.
40. The artist drew a beautiful portrait of the little boy.
41. I need to park my car soon so I can move it out of the way.

APPENDIX B GERMAN SENTENCE LIST

1. Heute ist schönes Frühlingswetter.
2. Die Sonne lacht.
3. Am blauen Himmel ziehen die Wolken.
4. Über die Felder weht ein Wind.
5. Gestern stürmte es noch.
6. Montag war es uns zu regnerisch.
7. Die Nacht haben Maiers gut geschlafen.
8. Jetzt sitzen sie beim Frühstück.
9. Es ist acht Uhr morgens.
10. Vater hat den Tisch gedeckt.
11. Mutter konnte länger schlafen.
12. Der Kaffee dampft in den Tassen.
13. Messer und Gabel liegen neben dem Teller.
14. In der Mitte steht der Brötchenkorb.
15. Ich möchte keinen Kuchen.
16. Hans ißt so gerneWurst.
17. Bald ist der Hunger gestillt.
18. Günther muß noch einkaufen gehen.
19. Sonst wirst du leicht überfahren.
20. Radfahrer sausen vorbei.
21. Im Geschäft stehen viele Leute.
22. Gleich hier sind die Nahrungsmittel.
23. Muß der Zucker nicht dort drüben stehen?
24. Jetzt suche ich das Weißbrot.
25. Ob ich Süßigkeiten kaufen darf?
26. Öl fehlte wohl auch.
27. Nun schnell nach Hause.
28. Vater will sich eine Pfeife anzünden.
29. Seine Frau macht ein trauriges Gesicht.
30. Du solltest weniger rauchen.
31. Aber Schönes steht wohl nicht drin.
32. Ich müßte lesen und rechnen.
33. Ich spüre ihn nicht mehr.
34. Wir wollen heute spazieren gehen.
35. Da möchte ich gerne mit.
36. Zuvor müssen wir uns stärken.
37. Die Kartoffeln gehören zum Mittagessen.
38. Können wir nicht Tante Erna besuchen?
39. Zurück geht's mit der Bahn.
40. Wir hören den plätschernden Bach.
41. Voller Glück sind wir am Ziel.
42. Die Tante bewohnt ein nettes Häuschen.
43. Manche Obstbäume blühen prächtig.
44. Der gelbe Küchenofen sorgt fürWärme.
45. Auf dem Brett leuchten bunte Tulpen.
46. Da läuft der Zug ein.
47. Leise rollen wir aus dem Bahnhof.
48. Draußen fliegt die Landschaft vorbei.
49. Hier richten Zimmerleute ein Dach.
50. Es gehört zu einer Feldscheune.
51. Nervöse Menschen brauchen viel Ruhe.
52. Unser Treffpunkt: Zwei Uhr am Neumarkt.
53. Heute jeder Strauß Blumen zwei Mark.
54. Du begrüßt erst Deinen Gast.
55. Schnupfen stört uns natürlich sehr.
56. Unsere Söhne lieben flotte Tänze.
57. Können Sie mir bitte das Buch ausleihen?
58. Ich hätte gerne ein Brötchen mit Schinken und Käse.
59. Das öffentliche Verkehrssystem in Berlin ist sehr gut.

60. Möchtest du lieber Tee oder Kaffee trinken?

ACKNOWLEDGEMENTS

The author thanks Priska, Irene, Christina, Timo, and Simons for their willingness to participate in the recording session, Prof. Studer-Joho Dieter for the recording equipment, and Prof. Ingrid Hove for her encouragement and inspiration.

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