Journal of
language | works

Vol. 10, No. 2, 2025

The Sound of Sleepiness:

A 24-hour sleep deprivation experiment, examining the relationship between Acoustic Vowel Space and sleepiness in sleep-deprived, Danish-speaking individuals

.

Josephine Gaia Lindquist
University of Copenhagen
JosephineGaiaLindquist@gmail.com / txw955@alumni.ku.dk

ABSTRACT

This study investigates the impact of short-term sleep deprivation on Acoustic Vowel Space (AVS), hypothesizing that Vowel Space Area (VSA) will shrink, with a more pronounced correlation with sleepiness, rather than simply the duration of wakefulness. Sleepiness levels were assessed using the Karolinska Sleepiness Scale, reaction time measurements, and performance in a memory task. Phonetic data were collected through semi-spontaneous speech tasks, using picture descriptions recorded in a controlled sound studio environment. Twelve native Danish speakers (aged 20–30) were monitored over a 24-hour period, with data collected at six-hour intervals. Variables such as individual sleep habits, substance use, and environmental influences were controlled for to ensure reliable results. On average, VSA decreased by 14.23% (p_adj =0.025) after 24 hours of wakefulness compared to baseline (after 6 wakeful hours), with 11 of 12 participants showing an overall reduction. Significant correlations were found between normalized VSA and two sleepiness markers: reaction time (p = 0.010) and self-reported sleepiness (p = 0.002), but not with memory-based markers. Notably, VSA correlated more strongly with hours awake past participants' usual bedtime (p = 0.000943) than with total hours awake (p = 0.0014), suggesting a hypoarticulatory sleepiness-related effect, rather than one driven by vocal fatigue.

Keywords: Acoustic Vowel Space (AVS), Vowel Space Area (VSA), Sleep-deprivation, Danish, Linguistics, Experimental Phonetics

1. Introduction

Sleepiness is a complex and multifaceted phenomenon, lacking a single, universally accepted unit of measurement. It has been described using both subjective and physiological measurements, which often depend on a combination of behavioral, self-reported, and biological indicators. Although it is widely recognized that sleepiness influences speech, its specific effects on phonetic output remain underexplored. Most existing studies have linked sleep deprivation to markers of vocal fatigue, such as lowered fundamental frequency (F_0) and increased jitter (Warthe & Sharma, 2022; Thoret et al., 2024), but few have examined the hypothesis that, as with other fine motor skills, articulatory precision may decline as the speaker becomes more tired. Without a clearer understanding of how sleepiness affects articulatory phonetic markers, there is a risk that results from speech production studies may be interpreted without adequate consideration of the speaker's cognitive and physical state.

One study, which may have been impacted by a lack of research in this field, is Weirich & Simpson (2023), which examined changes in new parents' phonetic markers during the peri- and postnatal period, focusing on how gender identity might influence these. Comparing Swedish and German mothers, a shrinking of the Acoustic Vowel Space (AVS) was found postnatally in German mothers only. It was concluded that these results indicated that gender-specific variation in speech is influenced by a culturally affected understanding of gender, and that Swedish speakers do not signal femininity through the same phonetic cues as German speakers. However, comparison of parental involvement between the two groups showed that Swedish fathers were significantly more involved in childcare than German fathers, whether or not they were on parental leave. This unequal division of labor was noted to have possibly contributed to maternal fatigue in German mothers, but despite mentioning that fatigue could have influenced the results, possibly causing a shrinking of AVS, this was not further explored.

The aim of this study is to contribute to our understanding of how sleepiness affects acoustic vowel space (AVS). Specifically, this project seeks to determine whether acute, short-term sleep deprivation leads to hypoarticulation, resulting in a reduction in Vowel Space Area (VSA). The analysis focuses on long, stressed vowel realizations of the Danish phonemes /i u æ a/, representing the language's corner vowels. Only tokens without *stød* – a suprasegmental feature in Danish involving a type of laryngealization – are included. Vowel productions affected by *r-coloring*, velar transitions, or coarticulation with the Danish *soft d* are also excluded from the analysis.[1]

Acoustic data are drawn from picture description tasks recorded over the course of a 24-hour sleep deprivation experiment. These data are used to test the central hypothesis: that VSA decreases progressively as the speaker becomes sleepier.

---

[1] These choices are justified in Section 2.3 *Coarticulation.*

2. Theory

2.1 Acoustic Vowel Space (AVS) and Vowel Space Area (VSA)

Acoustic Vowel Space (AVS) is a quantifiable manifestation of articulatory and acoustic variation in vowel production. It reflects physical changes in the dimensions of the vocal tract, primarily shaped by tongue movements. The quantification of this is known as Vowel Space Area (VSA) and is most commonly represented in a two-dimensional plane, with the first and second formants (F1 and F2) as coordinate axes (Kuo & Berry, 2023; Sandoval et al., 2013).

2.2 Phonetic Detail Under the Influence of Sleepiness

The hypotheses presented in this study are based on the assumption that the articulatory motor control involved in speech production is affected by sleepiness in much the same way as other motor functions of the body. Speech articulation is considered a fine motor skill (Rusz et al., 2019), and the expectation that AVS will decrease in size rests on the idea that this ability deteriorates under sleepiness, just as other fine motor abilities are known to do (Lee et al., 2001). This forms the basis for the hypothesis that AVS will shrink due to a predicted decline in articulatory precision when motor control of the speech organs is compromised.

For the purposes of this study, it is important that *sleepiness* is categorized separately from both *fatigue* and *vocal fatigue*. In this context, *fatigue* is defined as exhaustion resulting from sustained effort or activity, whether cognitive or physical. *Vocal fatigue,* as defined here, refers specifically to physical exhaustion of the speech organs following prolonged use. This differs from *sleepiness*, the sensation of feeling tired due to a lack of sleep.

A discussion of how these states may be analyzed separately is presented in the discussion.

2.3 Coarticulation

When choosing target words and collecting vowel tokens for the calculation of VSA, it was essential to account for the effects of coarticulation, as it may introduce challenges in vowel segmentation. The target words used in this study were specifically selected to avoid three particular phenomena that influence vowel formants and their transitions in ways that complicate acoustic analysis:

R-coloring, a phenomenon wherein a vowel articulated in the presence of /r/ assimilates to it, causing a decrease in the third formant, as well as an increase in the second formant of the vowel allophone (Nathan et al., 1998). According to Ejstrup & Hansen (2004b), the segmentation difficulties presented by allophones caused by the presence of /r/ arise from the fact that /r/ becomes a pharyngeal approximant in the prevocalic position, while postvocalically, it weakens to a semi-vowel, often assimilating entirely with the vowel preceding it.

The Danish *soft "d"* (/ð ɤ/) is traditionally considered to be a semivowel, and when combined with a vowel, it often results in a diphthong (Schachtenhaufen, 2023). This creates challenges in segmentation, as the transition between the vowel and the semivowel becomes unclear, and in some cases, the distinction becomes arbitrary (Grønnum, 2022).

Lastly, the *velar pinch* was also avoided in target word and vowel token selection. The term refers to the transitions characteristic of velar sounds, which involve a simultaneous rise in the second formant (F2) and lowering of the third formant (F3) as vowels approach or move away from a velar plosive, creating a "pinched" formant pattern in the neighboring vowel on a spectrogram (Zeller, 1997; Baker et al., 2008).

3. Procedure and Experimental Design

The study spanned a 24-hour period and included four data collection points, occurring every six hours from each participant's individual wake-up time. A total of 12 individuals participated in the study – 4 men and 8 women.

3.1 Participants

Twelve participants, aged 20 to 30, all native Danish speakers, were recruited from the researcher's personal network and participated voluntarily without compensation. All participants were informed that they would be taking part in a linguistic experiment about sleep deprivation and were made aware of the types of data being collected. However, they were not informed that phonetic analysis would be conducted on their picture descriptions, nor were they made aware of any specific hypotheses being tested.

Since sleepiness was a key variable, individuals with sleep disorders, daily use of sleep medication, or dependence on alcohol or narcotics were excluded. However, participants were allowed to maintain their usual individual consumption of caffeine and nicotine during their regular waking hours to avoid withdrawal symptoms. Prior to the day of the experiment, participants completed a questionnaire[2] about their sleep habits and caffeine and nicotine intake. This served both as a screening tool and to establish personalized guidelines for consumption during the experiment. Additionally, participants with prior experience in acoustic analysis were excluded, as their familiarity with the methods could influence their speech production and compromise the objectivity of the data.

Participants were informed that they could withdraw from the study at any time without consequence. They were also informed that if they chose to leave the study early, they would be offered a final data collection session, which they could decline without any repercussions.[3]

3.2 Ethical Considerations

During the conceptualization of the experiment, careful consideration was given to the ethical implications of subjecting participants to sleep deprivation, as it may cause discomfort. The study was designed in consultation with experts from the University of Copenhagen, including specialists in the humanities, medicine, and psychology. Emphasis was placed on participant safety through

---

[2] This questionnaire can be found at https://zenodo.org/records/17390396/files/Questionnaire.docx
[3] A copy of the consent form can be found at https://zenodo.org/records/17390396/files/Consent Form.docx

written informed consent, voluntary participation, and arranging for transport to ensure that no one had to drive after the study.

3.3 Elicitation Material

The elicitation material consisted of eight unique drawings specifically designed for this project. The drawings depicted various landscapes and contained clearly recognizable elements, each intended to elicit a word with a long, stressed corner vowel without *stød*. Corner vowels represent the extremes of the vowel phonemes in any one language, making them particularly suitable for measuring changes in the vowel space, the theoretical acoustic space wherein all vowel productions for a given speaker are expected to occur. The identification of corner vowels is language-specific and, in some cases, subject to debate. For the purposes of this study, the Danish corner vowels are defined as /i u æ a/.[4]

To ensure the best possible comparison with Weirich & Simpson (2023), semi-spontaneous speech was chosen as the data source for the study. Similarly, picture description was also chosen as the elicitation technique. This approach deliberately excluded all orthographic cues in the elicitation materials, as their presence would have induced a reading-aloud effect, which is not comparable to spontaneous or semi-spontaneous speech (Ejstrup & Hansen, 2004a, pp. 9–10). As in Ejstrup & Hansen (2004a), a central consideration in designing the elicitation materials was to select target words that were both familiar to the speaker and easily represented visually.[5]

---

[4] All eight elicitation-drawings can be found at https://zenodo.org/records/17390396/files/Elicitation Materials.docx
[5] A list of all 61 target words can be found at https://zenodo.org/records/17390396/files/Target Words.docx

Figure 1. One of the eight drawings used as elicitation material during the experiment's audio recordings. The drawing depicts a park and contains a total of 17 target words.

The drawings – such as one depicting a *park* /ˈpʰaːk/ in which a *dame* /ˈtæːmə/ with a *hale* /ˈhæːlə/ was walking her *due* /ˈtuːə/ (see Figure 1) – were deliberately peculiar in their composition. This was intended to draw participants' attention to elements in the drawings that did not naturally fit the landscape, thereby increasing the likelihood that the intended corner vowels would be elicited. Each drawing contained at least three target words for each of the corner vowels, and eight such drawings were created for the experiment to allow each participant two drawings per session, yielding a minimum of six tokens per vowel per session. Additionally, the order of presentation of the drawings was staggered to control for potential biases.

3.4 Procedure on the Day of the Experiment

On the day of the experiment, participants were instructed to wake up between 6:00 and 7:00 a.m. and to notify the experimenter immediately upon waking, so that their exact wake-up time could be recorded. This ensured that data collection occurred approximately every 6 hours from the time of waking. The data collections were evenly distributed throughout the 24-hour period, with the first data collection taking place six hours after each participant had woken up (approximately at 12 p.m.), and subsequent sessions following at six-hour intervals (at approximately 6 p.m., 12 a.m., and 6 a.m.).

The participants arrived at 10.00 a.m. and were instructed that they were free to occupy themselves as they wished throughout the day, provided they avoided the following:

- Consumption of alcohol or narcotics
- Consumption of caffeine or nicotine beyond their personal norm or past their usual bedtime
- Participation in physically exhausting activities
- Prolonged or uninterrupted talking, shouting, or singing
- Falling asleep

4. Data collection

Data collection was divided into two parts: an initial assessment of sleepiness, followed by the collection of phonetic data. Since the phonetic recordings were particularly sensitive to the experimenter's own level of tiredness, these sessions were conducted by two different individuals, one of whom was more well-rested. This approach was intended to minimize the risk that the experimenter's tiredness would lead to errors in data collection or inadvertently influence the participants' behavior, thereby affecting the results.

In the weeks prior to the experiment, each participant's sleep habits were documented using the previously mentioned questionnaire. At each data collection point, the total time awake, the number of hours awake past their usual bedtime, and the number of hours awake beyond their typical waking period were recorded.

Every aspect of the data collection procedure was consistently replicated across all four data collection points to ensure comparability.

4.1 Data Collection Part 1 – Sleepiness Assessment

Participants were invited individually into a private and comfortable room where they would not be disturbed. There, they were greeted by the experimenter, who introduced them to three tests, administered in the order described below.

4.1.1 Self-Assessment of Sleepiness

Perceived sleepiness was assessed using the Karolinska Sleepiness Scale (KSS) (Akerstedt & Gillberg, 1990), which ranges from 1 to 9 and includes descriptive labels for different degrees of sleepiness. The scale was presented in English, as previous studies underpinning the choice of this scale also used the English version (Shahid et al., 2011; Miley et al., 2016). To ensure a clear understanding among the Danish-speaking participants, a Danish translation – produced by me – was displayed side-by-side with the original scale, as shown in Figure 2.

Engelsk version

1	extremely alert
2	very alert
3	Alert
4	fairly alert
5	neither alert nor sleepy
6	some signs of sleepiness
7	sleepy, but no effort to keep awake
8	sleepy, some effort to keep awake
9	very sleepy, great effort to keep awake, fighting sleep

Dansk version

1	Ekstremt frisk
2	Meget frisk
3	Frisk
4	Temmelig frisk
5	Hverken helt frisk eller søvnig
6	Udviser nogle tegn på søvnighed
7	Søvnig, men behøver ikke anstrenge mig for at holde mig vågen
8	Søvnig, og må anstrenge mig noget for at holde mig vågen
9	Meget søvnig, det er en stor anstrengelse at holde mig vågen, og jeg må anstrenge mig for ikke at falde i søvn

Figure 2. The version of the Karolinska Sleepiness Scale presented to participants, shown in both the original English and Danish translation.

4.1.2 Reaction time test

Next, participants completed a visual detection task, as seen in Figure 3, designed to measure reaction time.[6] During the test, participants were instructed to press a gray square, which would then turn green, and to press the square again as soon as they noticed its color change to red. After a practice run, three timed trials were recorded by the experimenter. This procedure, including the practice trial, was repeated at all four data collection points.

[6] The script for the reaction time test, written in HTML, CSS, and JavaScript, can be found at https://zenodo.org/records/17390396

Figure 3. The visual detection task which was used to determine the participant's reaction time

4.1.3 Memory task

Finally, participants were presented with a virtual memory card game consisting of 12 pairs, illustrated in Figure 4.[7] At the start of each game, all cards were revealed face-up for 2 seconds to ensure that the first move was not purely random. Before each data collection, participants completed a brief practice round before playing the memory game twice, with both the number of attempts and the elapsed time recorded for each session.

To ensure variability and minimize practice effects, four different versions of the memory game – each featuring unique icons – were rotated so that no participant encountered the same version more than once during the study. To further reduce potential bias, the order in which the memory games were presented was staggered relative to the time of the data collection sessions.

[7] The scripts for the memory task, written in HTML, CSS, and JavaScript, are included in the data repository at https://zenodo.org/records/17390396

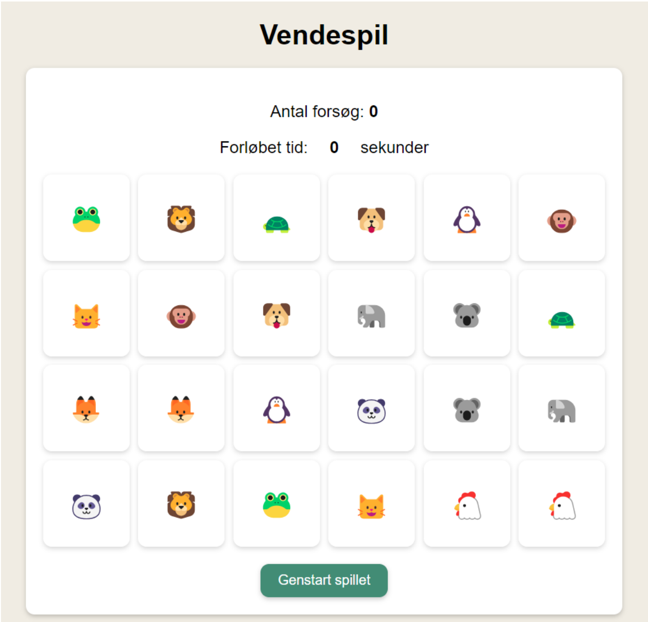

Figure 4. One of the four memory game variants completed by participants during the sleepiness assessments.

4.2 Data Collection Part 2 – Phonetic Data Collection

After completing the initial tests, the participant was brought into the recording studio. All electronic devices and loose jewelry were removed beforehand to avoid noise and interference during the recording session.

The microphone, a Sennheiser MKH 40-P48, was positioned at a sharp angle in front of the participant, approximately 40 cm from their face. Participants were instructed to keep their hands, body, and feet still throughout the session to minimize background noise. The input gain was adjusted to match the speaker's vocal level. Recording was carried out using *Audacity*, with settings configured for mono channel and a sample rate of 44.1 kHz. Once the setup was complete, the experimenter closed the studio door and sat directly across from the speaker, approximately two meters away, to reduce the risk of introducing noise through their own presence.

Participants were presented with one of the eight specially designed elicitation images and instructed to describe everything they could see in the picture to the experimenter. The experimenter did not interrupt the speaker but occasionally made informal comments during silences to support a conversational dynamic and to encourage more natural speech. Each participant was shown two images per data collection session. While the image descriptions were ongoing, the experimenter discreetly took notes to track the number of occurrences of each target phoneme by tracking which target words had been produced. To avoid drawing attention to the target words – and thus interfering with the natural flow of speech – pseudo-notes were also taken between actual annotations. If, after the two image descriptions, the participant had not yet produced at least six instances of target words for each corner vowel, the experimenter was permitted to ask open-ended, non-leading questions about the image to elicit further speech.

5. Analyzing the Phonetic Data

The experiment was carried out as planned, with participation from 12 subjects, all of whom completed four data collection sessions. These sessions were evenly distributed across a 24-hour period at six-hour intervals, having been scheduled according to each participant's individual wake-up time, ensuring that testing occurred at their 6th, 12th, 18th, and 24th hour of wakefulness.

Initially, 15 potential participants were screened to ensure they met the inclusion criteria. Three were excluded: one due to a diagnosed sleep disorder, one due to illness on the day of testing, and one who had not slept the night before the experiment began. These exclusions were made to minimize the risk of bias and ensure a consistent and reliable data set.

5.1 Data Processing

The experiment resulted in a substantial amount of data, including 144 reaction time tests, 48 self-assessments of sleepiness, and 1,774 vowel segments, extracted from 48 .wav files with a total duration of 25,390 seconds.[8]

5.1.1 Transcription

To facilitate the identification of target words within the audio files, all recordings were first transcribed using Whisper AI (OpenAI, 2022) via a script written for Praat by Gert Foget Hansen (*Whisper_in_Praat_v0.8.2*, 2024)[9]. However, the automatic transcriptions proved highly unreliable. Therefore, a manual check was performed to identify and correct incorrect transcriptions of target words. An additional manual review was conducted to ensure that the marked target words actually contained a long, stressed corner vowel without *stød*.

5.1.2 Segmentation

Each elicitation of a target word was examined to identify and segment the target vowel, which was then evaluated for suitability based on the following criteria, selected to align with general standards within phonetic analysis:

- **Segment duration:** A minimum of 30 milliseconds.
- **Number of oscillations**: A minimum of 5 oscillations.
- **Formant consistency**: Consistent formant values across the segment according to visual inspection of formant placement in the spectrogram and, where necessary, LPC analysis.

[8] All anonymized non-phonetic data on the participants can be found at https://zenodo.org/records/17390396/files/All Non-Phonetic Participant Data ANONYMOUS.xlsx

[9] A copy of this script can be found at https://zenodo.org/records/17390396/files/Whisper_in_Praat_v0.8.2.psc

In total, 1,774 vowel segments were deemed suitable and were included in the analysis.

5.1.3 Formant Measurement

Formant frequency measurements were carried out using a Praat script written by Nicolai Pharao (*measureF1F2F3F4.praat*), which I modified for this study.[10] The modified script measured and recorded the average frequencies of the first two formants in the segmented tokens of the corner vowels, along with the duration of each segment (see Table 1).[11] [12]

Wakeful Hours	Participant	Vowel	F1_mean (Hz)	F2_mean (Hz)	Duration (milliseconds)
6	T1	a:	904	1502	76,80938212
6	T1	a:	966	1342	84,99398841
6	T1	a:	738	1781	113,9949856
6	T1	a:	876	1624	84,25716327
6	T1	a:	799	1632	109,0386819
6	T1	a:	900	1322	73,66145662
6	T1	a:	834	1436	61,06975463
6	T1	a:	794	1520	99,47444569
6	T1	a:	837	1471	116,3424061
6	T1	a:	818	1500	67,86640357
12	T1	a:	891	1265	109,2903666
12	T1	a:	846	1568	73,57456055

Table 1. Excerpt from the collected phonetic data.

Measurements were performed individually for each participant and separately for instances of /uː/ and /iː æː aː/. This allowed a specific formant ceiling to be set for /uː/ to ensure reliable and consistent measurements.

5.2 Methods for Data Analysis

The Vowel Space Area (VSA) was calculated geometrically by constructing a polygon from the average formant values of the selected vowels and measuring its area. The area of the polygon formed by connecting these average vowel points was calculated in square Hertz.

All data analyses were conducted using R, version 4.3.3 (R Core Team, 2024), and all statistical tests were conducted using linear models in the form:

---

[10] These scripts are included in the data repository at https://zenodo.org/records/17390396

[11] The distribution of the collected vowel tokens – both in number of observations and in segment duration – is provided at https://zenodo.org/records/17390396/files/Distribution of Vowel Tokens.png

[12] The complete phonetic dataset can be found at https://zenodo.org/records/17390396/files/All Phonetic Data.xlsx

$$y = \alpha + \beta \cdot x + \varepsilon$$

for continuous data, and

$$y_i = \alpha + \beta_i \cdot x_i + \varepsilon_i$$

for categorical data, where y is the dependent variable (in this case, VSA or normalized VSA), x is the independent variable, ε is the residual error term, and i indexes the levels of the categorical variable. Model fitting was carried out in R using the $lm()$ function.

These models were used to assess whether statistically significant relationships existed between vowel space and various sleepiness markers, not to prove a linear correlation. As such, the coefficient of determination (R^2) is considered less informative than the p-values, which more directly reflect statistical significance.

For models involving categorical data with multiple levels, post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to adjust for multiple comparisons. This was performed using the $TukeyHSD()$ function in R.

6. Results

6.1 Changes in VSA Across the Sleep-Deprived 24-Hour Period

To test the hypothesis that VSA shrank over the sleep-deprived period, a categorical linear model was applied, comparing participants' VSA at the 6th and 24th wakeful hours. Using a categorical model ensured that only these discrete time points were compared, without imposing a linear relationship on the data. This analysis revealed an overall reduction in VSA of 14.23%[13] (p_{adj}[14] $= 0.025$) across all participants.

Eleven of the twelve participants showed a decrease in VSA from the 6th to the 24th hour of wakefulness. For five participants, the lowest VSA was recorded at hour 24. Among the remaining seven, four showed a continuous decline in VSA across the first 18 hours, followed by an increase in the final measurement. An overview of the percentual change in VSA for all participants can be seen in Table 2.

[13] Calculated using the linear model for categorical data outlined in Section 5.2.
[14] Adjusted for family-wise error rate, med Tukey's Honest Significant Difference test.

Participant	VSA change 12h (%)	VSA change 18h (%)	VSA change 24h (%)	Overall change (%)
T1	+11.12	-0.91	-20.05	-11.98
T2	+13.16	-24.34	-38.21	-47.10
T3	+3.74	-4.31	-15.88	-16.49
T4	-4.23	+22.30	-14.64	-0.01
T5	+23.74	-22.70	-8.09	-12.08
T6	-12.77	-10.02	+16.88	-8.27
T7	-9.00	-20.15	+40.13	+1.82
T8	+7.00	-15.06	-14.46	-22.26
T9	-4.18	-2.66	-18.88	-24.33
T10	-11.03	-15.69	+25.94	-5.50
T11	-28.98	+17.20	-1.57	-18.07
T12	-3.17	-9.07	+6.20	-6.50

Table 2. Overview of the percentual change in VSA per participant, per data collection.

In total, nine out of twelve participants (75%) exhibited their smallest vowel space during the sleep-deprived period, compared to measurements taken during the hours they would normally be awake.

Each vowel symbol in the VSA diagrams represents a single instance of a long, stressed vowel without *stød*. The crosses indicate the average position of all observed tokens for a given vowel at each data collection point, color-coded according to wakefulness duration.

The largest change in vowel space was observed in participant T2, with a total VSA reduction of 47.1% (see Figure 5). This participant showed a continuous decline beginning at the 12th hour of wakefulness, with the most substantial drop occurring between hours 18 and 24, where a decrease of 38.21% was recorded.[15]

[15] All AVS and correlation charts, along with their statistical data, are available at https://zenodo.org/records/17390396/files/All Statistical Data.docx. A full comparative chart of all twelve AVS's can also be found at https://zenodo.org/records/17390396/files/VSA of all Participants.svg

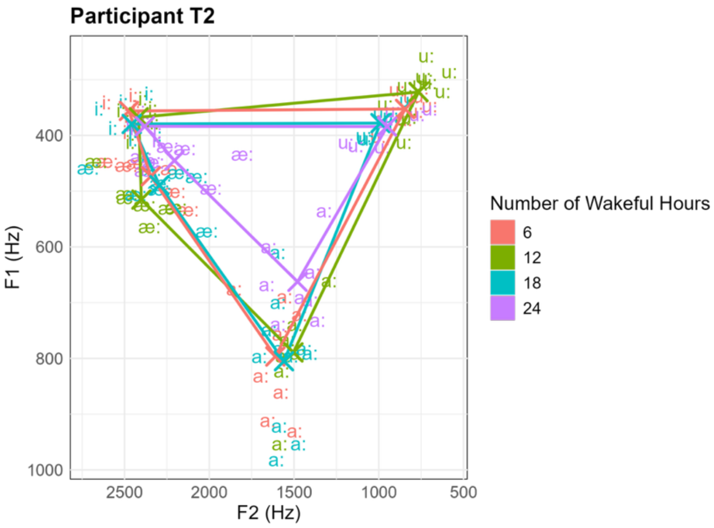

Figure 5. VSA for participant T2 at each 6-hour interval: 6th hour: 382,497.16 Hz², 12th hour: 432,815.11 Hz² (+13.16%), 18th hour: 327,478.71 Hz² (-24.34%), 24th hour: 202,357 Hz² (change: -38.21%). Total overall change: -47.1%.

In contrast, participant T7 (Figure 6) – the only participant who showed an overall increase in VSA (+1.82%) – exhibited a more complex pattern. VSA consistently declined until the 24th hour of wakefulness, at which point a sharp increase of 40.13% was recorded compared to the measurement directly preceding it.

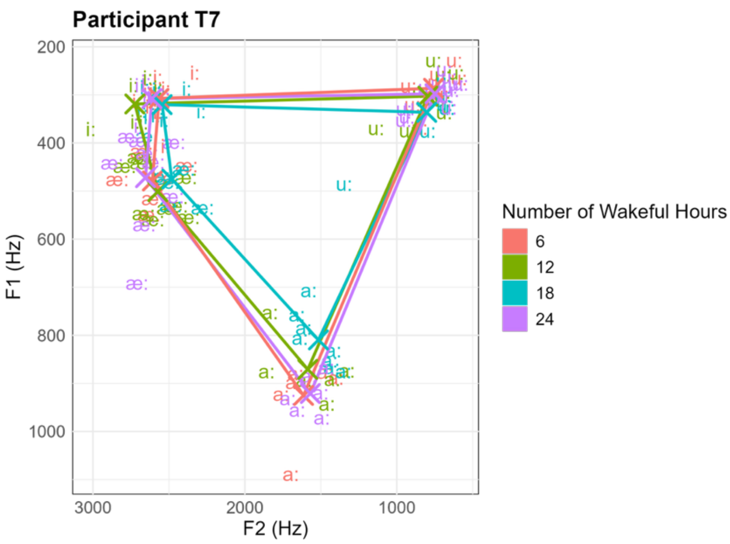

Figure 6. VSA for participant T7 at each 6-hour interval: 6th hour: 663,298.57 kHz², 12th hour: 603,607.44 kHz² (-9%), 18th hour: 481,965.53 kHz² (-20.15%), 24th hour: 675,368.86 kHz² (+40.13%). Total overall change: +1.82%.

For more than half of the participants, the smallest measured VSA did not occur at the 24th hour of wakefulness. In four of these seven cases, the minimum VSA was observed at hour 18. For the remaining three participants (25%), the smallest vowel space occurred during their typical waking hours, rather than during the sleep-deprived period, as seen in Table 2.

Potential explanations for these variations are discussed in Section 7.

6.2 Correlations between sleepiness markers and VSA

To test the correlation between the observed changes in VSA and the sleepiness markers, all markers were analyzed against normalized VSA using continuous linear models, reflecting the continuous nature of the sleepiness markers as independent variables.

Statistical analysis reveals that all but one category of sleepiness markers used in the study show a significant negative correlation with normalized Vowel Space Area (VSA). Neither time spent per game nor the number of attempts in the memory task showed a significant relationship with VSA. In contrast, average reaction time (Figure 7) and self-reported sleepiness on the Karolinska Sleepiness Scale (KSS) (Figure 8) were both significantly correlated with VSA, with p-values of 0.014 and 0.002, respectively.

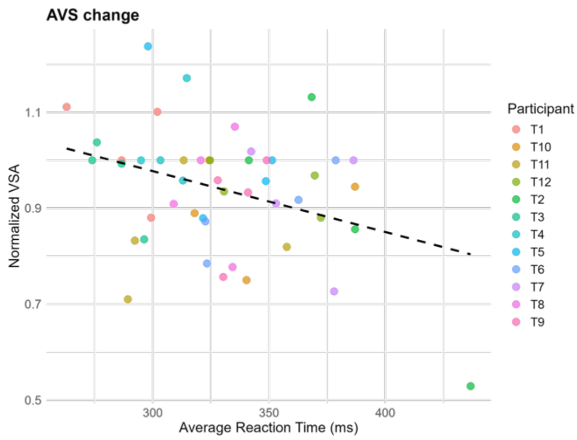

Figure 7. Linear modeling of the correlation between normalized VSA and average reaction time ($\beta = -0.0013$, $SE = 0.0005$, $p = 0.014$, $R^2 = 0.1246$, adjusted $R^2 = 0.1056$).

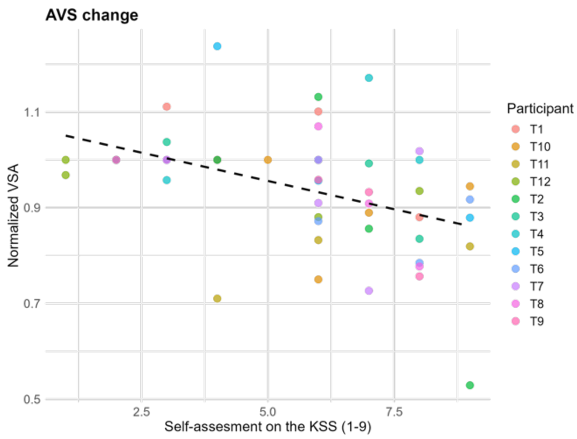

Figure 8. Linear modeling of the correlation between normalized VSA and self-assessments on the KSS ($\beta = -0.024$, SE = 0.0073, $p = 0.002$, $R^2 = 0.187$, adjusted $R^2 = 0.1689$).

This indicates that participants' vowels became increasingly hypoarticulated as their subjective sleepiness rose and as a performance-based measure of sleepiness worsened.

The most significant correlations, however, were found among the sleep-schedule-related markers. The number of wakeful hours was found to have a highly significant correlation to changes in VSA ($p = 0.0014$) (see Figure 9), as did the number of hours beyond the usual number of wakeful hours, as shown in Figure 10 ($p = 0.00374$). However, the single most significant predictor of VSA was found to be the number of wakeful hours beyond the participants' usual bedtime ($p = 0.000963$), see Figure 11.

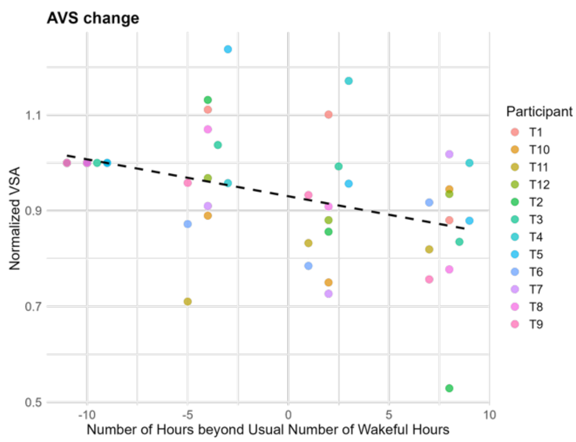

Figure 9 Linear modeling of the correlation between normalized VSA and number of wakeful hours ($\beta = -0.0085$, SE = 0.0025, $p = 0.0014$, $R^2 = 0.2004$, adjusted $R^2 = 0.183$).

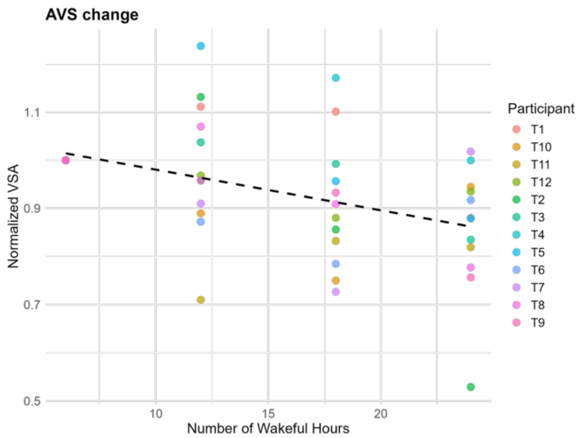

Figure 10 Linear modeling of the correlation between normalized VSA and number of hours beyond usual number of wakeful hours ($\beta = -0.007714$, SE = 0.002525, $p = 0.00374$, $R^2 = 0.1687$, adjusted $R^2 = 0.1506$).

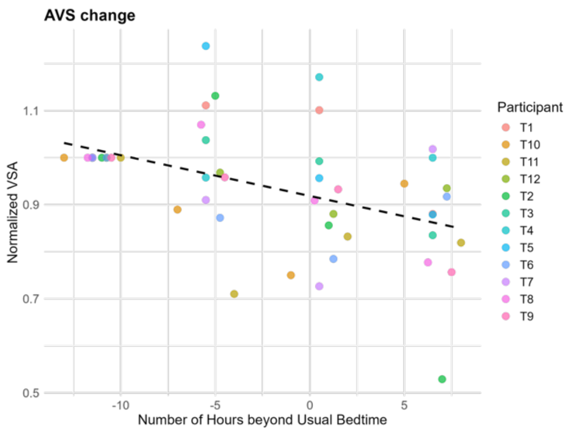

Figure 11 Linear modeling of the correlation between normalized VSA and number of hours beyond usual bedtime ($\beta = -0.008659$, SE = 0.002455, $p = 0.000963$, $R^2 = 0.2129$, adjusted $R^2 = 0.1958$).

This shows that vowel sounds became increasingly hypoarticulated the longer participants remained awake, with the effect being even more pronounced for vowel sounds produced during periods where the participants usually would have gone to bed.

7. Discussion

The results of this study indicate that AVS decreases in size as speaker sleepiness increases, with two of four non-sleep-schedule-related sleepiness markers showing significant negative correlations with normalized VSA. This relationship is strongest for hours awake beyond participants' usual bedtime, compared to total wakeful hours or additional hours beyond the typical wakeful duration. This suggests that it is primarily the cognitive and physiological consequences of sleep deprivation – that is, the experience of feeling sleepy – rather than mechanical fatigue of the speech organs, that have a measurable impact on VSA.

A notable trend is an increase in VSA after the 18th wakeful hour: just over half of participants who did not show their lowest VSA at hour 24 experienced a drop in VSA at hour 18, as seen in Table 2. This deviation from the expected linear decline in VSA suggests that factors beyond sleepiness alone may have influenced the results. A plausible explanation is performance pressure, possibly arising from participants being aware that the final measurement took place at hour 24, likely resulting in an adrenaline boost and improved articulation and response time. The phenomenon of a "second wind" may also have played a role, where extreme sleep deprivation triggers a temporary state of hyperactivity due to the body's circadian rhythm (Bryan & Guo, 2024). The fact that the sun was rising during the final measurements may have further influenced the participants' energy levels.

Several potential sources of error should be considered when interpreting the results. The number of data collections was limited by practical constraints, including time requirements and the capacity of the recording studio. The collected self-assessment data showed notable linearity, and comments from participants such as "What did I rate myself last time?" suggest that participants may have based their ratings on expectations of gradual change rather than on actual experienced sleepiness.[16] In addition, a practice effect may have influenced test outcomes, as repeated execution of the memory and reaction tasks likely improved participants' performance independently of their level of sleepiness.

The observed relationship between VSA and sleepiness supports Weirich and Simpson's (2023) hypothesis that lack of sleep can lead to hypoarticulation and reduced AVS. This raises a methodological concern for studies that rely on AVS as a data source without accounting for sleepiness and fatigue. However, it remains unclear whether short-term sleep deprivation – as examined in this study – can be directly compared with the prolonged physical and mental exhaustion observed in Weirich and Simpson (2023). Their participants likely experienced fatigue developing over weeks or months, whereas this study specifically avoided effects from prolonged physical and cognitive exhaustion. While my results confirm a relationship between sleepiness and reduced VSA, it cannot be ruled out that long-term sleepiness or chronic sleep restriction would result in a different developmental pattern in AVS.

Overall, these findings provide strong evidence that Acoustic Vowel Space is sensitive to sleepiness and sleep deprivation, supporting the hypothesis that articulatory precision declines as speakers grow more tired. This highlights the potential of AVS as a marker for monitoring sleepiness and suggests that phonetic research using AVS as a variable should not be interpreted independently of the speaker's cognitive and physiological state.

---

[16] For future uses of a scale such as the KSS, asking the participants if they identify with the description of the most neutral score, adjusting based on their response, and noting the description that they find best suited, should be considered in place of presenting the participants with the scale itself.

8. Conclusion

The aim of this study was to investigate whether Acoustic Vowel Space (AVS) decreases in size during sleep deprivation, and whether this change correlates more closely with sleepiness markers than with the total number of wakeful hours. After 24 hours of wakefulness, VSA decreased by an average of 14.23% ($p_{adj} = 0.025$), with 11 of 12 participants showing reductions between the 6th and 24th hour.

Significant negative correlations were observed between VSA and multiple sleepiness markers: total hours awake ($p = 0.00014$), average reaction time ($p = 0.014$), self-rated scores on the Karolinska Sleepiness Scale (KSS) ($p = 0.002$), as well as the number of hours awake beyond both the participant's typical waking hours ($p = 0.00374$) and usual bedtime ($p = 0.0000963$). No significant correlation was proven between VSA and memory-based markers. Notably, VSA correlated more strongly with the number of hours awake beyond participants' usual bedtime than any other sleepiness marker, suggesting that the observed hypoarticulation was driven by sleepiness, rather than vocal fatigue.

Contrary to expectations, the study observed an unexpected increase in VSA after the 18th hour awake, which may be related to performance pressure and a "second wind" effect. This observation showed significant correlation with sleepiness markers, indicating that sleepiness is more complex than can be measured solely by the number of wakeful hours, and that VSA captures some of this complexity. Expanding the study with additional data collection points could provide a more nuanced understanding of this pattern.

9. Acknowledgements

This research would not have been possible without the time and dedication of my dear friends, who served as test subjects. This project is dedicated to you.

I would also like to extend my sincere gratitude to Nicolai Pharao, Associate Professor in Linguistics at the University of Copenhagen, for his guidance and insight throughout the development of this project.

Reference List

Akerstedt T, Gillberg M. (1990). Subjective and objective sleepiness in the active individual. International Journal of Neuroscience, 52, 29–37. https://doi.org/10.3109/00207459008994241

Baker, A., Mielke, J., & Archangeli, D. (2008). More velar than /g/: Consonant coarticulation as a cause of diphthongization. In C. B. Chang & H. J. Haynie (Eds.), Proceedings of the 26th West Coast Conference on Formal Linguistics, 60-68. Somerville, MA: Cascadilla Proceedings Project. https://www.lingref.com/cpp/wccfl/26/paper1656.pdf

Bryan, L., & Guo, L. (2024, March 15). Circadian rhythm. Sleep Foundation. https://www.sleepfoundation.org/circadian-rhythm

Ejstrup, M., & Hansen, G. F. (2004a). Vokaler I tre regionale varianter af Dansk. Master's Thesis, University of Copenhagen, 7-100.

Ejstrup, M., & Hansen, G. F. (2004b). Vowels in regional variants of Danish. Proceedings FONETIK 2004, Stockholm University, 88-91. https://www.diva-portal.org/smash/get/diva2:176795/FULLTEXT01.pdf#page=88

Ekrem, D. (2022). Why You Can't Remember Where Your Keys Are: The Effects of Sleep Deprivation on Visual Short-Term Memory. International Journal of High School Research, 4(4), 36–39. https://doi.org/10.36838/v4i4.7

Fox, R. A., & Jacewicz, E. (2017). Reconceptualizing the vowel space in analyzing regional dialect variation and sound change in American English. The Journal of the Acoustical Society of America, 142(1), 444–459. https://doi.org/10.1121/1.4991021

Grønnum, N. (2022). Conventions for segmental transcription. DanPASS. https://www.danpass.hum.ku.dk/links_2014/conventions/segmental_transcription.pdf

Hansen, G. (2024). Whisper in Praat v0.8.2 (Windows & macOS). http://dx.doi.org/10.13140/RG.2.2.24093.93925

Kuo, C., & Berry, J. (2023). The Relationship Between Acoustic and Kinematic Vowel Space Areas With and Without Normalization for Speakers With and Without Dysarthria. American Journal of Speech-Language Pathology, 32(4S). https://doi.org/10.1044/2023_AJSLP-22-00158

Lee, H., Song, H., Ham, B., Suh, K., & Kim, L. (2001). Effects of total sleep deprivation on fine motor performance. Sleep Medicine and Psychophysiology, 8(2), 129–137. https://www.koreascience.or.kr/article/JAKO200115750715092.pdf

Lindquist, J. (2023). Supplerende forsøgsforslag: Effekten af kortvarig søvndeprivation på akustiske parametre for sibilanter. Unpublished exam, Akustisk Analyse E23, University of Copenhagen.

Miley, A. Å., Kecklund, G., & Åkerstedt, T. (2016). Comparing two versions of the Karolinska Sleepiness Scale (KSS). Sleep and Biological Rhythms, 14(3), 257–260. https://doi.org/10.1007/s41105-016-0048-8

Nathan, G. S., Ladefoged, P., & Maddieson, I. (1998). The Sounds of the World's Languages. Language, 74(2), 313. https://doi.org/10.2307/417875

OpenAI. (2022). Whisper AI: Speech recognition model.

R Core Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rusz, J., Vaneckova, M., Benova, B., Tykalova, T., Novotny, M., Ruzickova, H., Uher, T., Andelova, M., Novotna, K., Friedova, L., Motyl, J., Kucerova, K., Krasensky, J., & Horakova, D. (2019). Brain volumetric correlates of dysarthria in multiple sclerosis. Brain and Language, 194, 58–64. https://doi.org/10.1016/j.bandl.2019.04.009

Schachtenhaufen, R. (2023). Utilpasset IPA. Danske Studier, 48-49. https://doi.org/10.7146/danskestudier.vi2023.146735

Shahid, A., Wilkinson, K., Marcu, S., & Shapiro, C. M. (2011). Karolinska Sleepiness Scale (KSS). STOP, THAT and One Hundred Other Sleep Scales, 209–210. https://doi.org/10.1007/978-1-4419-9893-4_2

Thoret, E., Andrillon, T., Gauriau, C., Léger, D., & Pressnitzer, D. (2024). Sleep deprivation detected by voice analysis. PLOS Computational Biology, 20(2), e1011849–e1011849. https://doi.org/10.1371/journal.pcbi.1011849

Tukey, J. W. (1949). Comparing individual means in the analysis of variance. Biometrics, 5(2), 99–114. https://doi.org/10.2307/3001913

Warthe, A. B., & Sharma, V. (2022). Changes in speech and voice characteristics following two hours and eight hours of acute sleep deprivation. Indian Journal of Aerospace Medicine, 66, 15–20. https://doi.org/10.25259/ijam_18_2020

Weirich, M., & Simpson, A. P. (2023). Changes in parents' phonetic parameters during the first year of a child's life. Comparative study of German and Swedish, Proceedings of the 20th ICPhS, 1-5. https://www.internationalphoneticassociation.org/icphs-proceedings/ICPhS2023/full_papers/54.pdf

Zeller, C. (1997). The investigation of a sound change in progress: /æ/ to /e/ in Midwestern American English. Journal of English Linguistics, 25(2), 142-155. https://doi.org/10.1177/007542429702500207