INTERSPEECH 2023
20-24 August 2023, Dublin, Ireland

Identifying Stable Sections for Formant Frequency Extraction of French Nasal Vowels Based on Difference Thresholds

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Abstract

Formant frequencies of a vowel are generally extracted from midpoints or central sections on the time axis. Nasal vowels present a challenge for obtaining stable formant frequencies, as the midpoint often falls in an anti-formant section where vocal energy is lost through the nasal cavity. This study proposes a stable section for extracting nasal vowel formant frequencies using difference thresholds, which identify a vowel as being distinct when F1 is above 60 Hz and/or F2 is above 200 Hz. For the experiment, 481 disyllabic words (232 nasal vowels and 294 oral counterparts) are selected from an online French-Korean Dictionary. Each vowel is divided into 10 intervals, and the stable section is identified as one or more continuous intervals with lower frequencies than the difference thresholds. The results show that the stable section for nasal vowels is identified in 20%~50% of the vowels, while the stable section for oral vowels is identified in 20%~80% of the vowels.

Index Terms: stable section, formant frequency values, French, nasal vowels, difference threshold

1. Introduction

Research on determining the boundary between a consonant and its following vowel or between a vowel and its following consonant has been carried out by using terms such as "dynamic formants (formant movements)" [1], "formant transition (variation)" [2] and "co-articulation" [3, 4]. According to [5], the sections of the vowel that are not undergoing a formant transition are considered stable, and the optimal value of the formant frequency can be obtained in these stable sections.

There are three types of methods to extract the formant frequencies of vowels. The first type involves taking the values at the midpoint or mid-section based on the time axis. According to [6] and [7], the midpoint is the point at which a vowel is least affected by adjacent consonants. The midpoint was very often used in earlier works [8, 9, 10, 11]. Some studies have considered the midpoint's 25% range to be stable [12], while others have considered the 25ms or 25ms to 50ms range at the midpoint to be stable [13, 14].

The second type involves determining values at specific points within the vowel, rather than at the midpoint or mid-section. [15] proposes to measure the frequency values at 1/3 and 2/3 of the vowel's length, while [16] measures the frequency values at 1/3, 1/2, and 2/3 points. There are other studies in which the frequency values are measured at various points in the range from 20% to 80% [17, 18, 19, 20]. [17, 18] measure the frequency values across the entire range of 20% to 80%, while [19] measures at the 20%, 50%, and 80% points. Finally, [20] measures at the 20%, 35%, 50%, 65%, and 80% points.

[21] regards the vowel's starting point and midpoint to be stable, while [22, 23] considers 'per 20ms', or 'the first 20ms, midpoint, and last 20ms' of the vowel to be stable. [24] considers the 40ms after the onset burst and the 40ms before the offset of the final consonant to be stable. [25] regards the first 30ms and last 40ms of the vowel to be stable. Lastly, [26] regards the midpoint and endpoint for V1 and the starting point and midpoint for V2 in V1.CV2 to be stable. However, [27, 28] challenge the assumption that a temporally stable (or fixed) formant pattern always appears in all vowels.

The third approach involves selecting a specific point along the vertical axis of the spectrogram to extract the formant frequency values. [29, 30] extract the maximum point on the F1 trajectory, while [31] uses the maximum point for F1 and the midpoint for F2. [7] uses either the minimum or maximum values of F1 and F2, and [32] considers certain frequency values to be stable for each vowel, such as the maximum of F2 for /i/ and the minimum of F2 for /u/.

These studies share three main characteristics. Firstly, the majority of them measure formant frequency values at the midpoint or within the midpoint region along the spectrogram's time axis. Secondly, most of them use read speech data, while a few use spontaneous speech data, such as [8, 22]. According to [4, 33, 34], stable sections of vowels are easier to obtain in read speech because the reduction of vowels or variation due to co-articulation with the preceding consonant appears more frequently and longer in spontaneous speech. Thirdly, the studies deal with various different languages, including English (16), Japanese (1), Swedish (1), Italian (1), Arabic (1), Kannada (1), German (1), and French (3). Among these languages, nasal vowels only exist in French, but even for French, [8, 10] focuses on oral vowels, while [9] investigates French nasal vowels and measures the formant frequency values at the midpoint.

Nasal vowels present a challenge for obtaining stable formant frequencies, as the midpoint often falls in an anti-formant [35] section where vocal energy is lost through the nasal cavity. According to [36], nasal vowels are divided into two sections based on their acoustic properties as shown in Figure 1: the oral vowels section (to the left of the solid red line), and the nasal and nasalized vowels section (to the right of the solid red line). Figure 1 presents the spectrograms of French nasal vowels /ɑ̃/, /ɛ̃/, and /ɔ̃/ preceded by bilabial voiced stop [b]. Nasal vowels are produced when some of the vocal energy passes through the oral cavity, and the remaining energy simultaneously passes through both the oral and nasal cavities, due to the lowered soft palate, leading to the flow of air through the nose. The lack of consistent correspondence between formants in the oral cavity for oral vowels and the spectral peaks observed on spectrograms for nasal and nasalized vowels is due to the presence of anti-formants that appear in the nasal and nasalized vowel sections.

As pointed out in [36], extracting the formant frequency values of vowels at the midpoint for nasal vowels may raise questions about the reliability of the values in nasal vowels due to the presence of

10.21437/Interspeech.2023-498

anti-formants appearing in the nasalized oral vowel and nasal consonant sections.

As in Figure 1, the midpoint of all three French nasal vowels, the dotted lines marked by the authors, belongs to the anti-formant region, presented in red lines [36]. It shows that the midpoint does not seem to correspond to any stable sections. This study proposes a stable section for extracting formant frequencies of French nasal vowels /ɛ̃, ɑ̃, ɔ̃/ along with their corresponding oral vowels /ɛ/, /a/, and /ɔ/using difference thresholds proposed in earlier studies. Then the frequency values extracted by the proposed method are compared to those measured at mid-points.

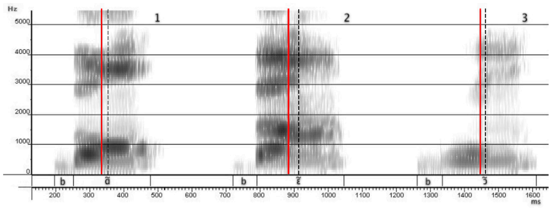

Figure 1. *Spectrograms of the French syllables [bɑ̃], [bɛ̃], and [bɔ̃] [36, p. 205]: The red lines represent the start points of the anti-formant in [36], while the dotted lines correspond to the midpoint, marked by the authors.*

The remainder of the paper is organized as follows. Section 2 reviews previous studies on the difference thresholds. Section 3 describes the corpus employed for the experiment, and a method for identifying the stable section of nasal vowels is proposed based on the difference thresholds. Section 4 presents the results of the proposed method on the French nasal vowels /ɛ̃, ɑ̃, ɔ̃/ and the oral vowels /ɛ, a, ɔ/, followed by a comparison of F1 and F2 measured in stable sections and at midpoints. Finally, the conclusion is drawn in Section 6.

2. Difference Thresholds

According to [37], the difference threshold (also known as the Just Noticeable Difference) refers to the smallest perceptual change in a stimulus that a listener can detect. It is a crucial concept in understanding auditory perception and has been used in various speech perception experiments. Perceptual experiments on synthesized vowels have shown that the difference thresholds for F1 are 60 Hz and 176 Hz for F2, respectively [38, 39, 40].

Acoustic studies [41, 42] use the difference threshold of F1 as a criterion for identifying phonetic contrasts of vowels in the English dialects of Northern and Southern Canada, which were collected through interviews. A vowel was considered acoustically distinct if the difference in F1 was greater than 60 Hz. [43] conducted an acoustic experiment to compare the performance of two software tools, Praat and Snack, for Northern and Southern French languages in large corpora, such as the Phonology of Contemporary French (PCF) corpus and Conversational Telephone Speech (CTS) corpus. In [43], difference thresholds of 63 Hz for F1 and 113 Hz for F2 were reported for vowel formant measures. [44] used difference thresholds to reanalyze existing results on the acoustic correlates of American English stress, and showed that the difference thresholds for F0, F1, and F2 are within the range of the existing ones. This suggests that difference thresholds are useful for identifying acoustic correlates of English stress. Finally, [45] employed difference thresholds to investigate the perceptual limits of various L2 English speech sounds for non-native listeners, which showed that the difference threshold for F1 is greater than 60 Hz and for F2 greater than 200 Hz. The study concludes that the difference thresholds for physical and acoustic differences are relevant to all languages, not only English, due to similar language processing capabilities.

In reference to [38~45], the widely accepted difference threshold for F1 is 60 Hz, while there is no consensus regarding the difference threshold for F2. According to auditory perception [38~40], the difference threshold for F2 was found to be 176 Hz, based on acoustic measurement [43] it was 113 Hz, and from the perspective of L2 teaching-learning [44, 45], it was determined to be 200 Hz.

In this study, we propose a stable section adopting the difference threshold of [44, 45] as an alternative to the limitations encountered in the formant frequency extraction of nasal vowels.

3. Method

3.1. Corpus

A total of 481 disyllabic words are selected from the NAVER French-Korean online dictionary [46] provided by the Korean portal search engine NAVER, which is designed specifically for Korean learners of French. Each word in the dictionary is provided with a sound file recorded by a native voice actress who speaks standard French. The selected words are of the C1V1.C2V2 structure with a stop consonant in the syllabic onset position. There are three nasal vowels in standard French, /ɛ̃, ɑ̃, ɔ̃/, whose corresponding oral vowels are /ɛ, a, ɔ/. We will investigate the stable section of these French nasal vowels based on difference thresholds along with their corresponding oral vowels.

The total number of nasal vowels is 232 (/ɛ̃/ 60, /ɑ̃/ 87, and /ɔ̃/ 85) and that of corresponding oral vowels 249 (/ɛ/ 68, /a/ 101, and /ɔ/ 80), all appearing in the initial syllable (V1). The onset and offset points of F1 and F2, as well as vocal fold vibration (pulse) are considered in order to determine the vowel boundaries using Praat. The statistical analysis of resulting measurements is conducted using an independent sample t-test in SPSS.

3.2. Identify Stable Sections Based on Difference Thresholds

According to [45], the difference threshold for F1 is 60 Hz and for F2 it is 200 Hz. A stable section will be identified by using these two difference thresholds by following three steps. An example of each step is provided using the nasal vowel /ɑ̃/.

Step 1. Divide a given vowel into 10 intervals and extract F1 and F2 values

As in the case of the nasal vowel /ɑ̃/ in Table 1, the vowel is divided into 10 intervals on the time axis, and F1 and F2 values for each interval end point are extracted by using Praat.

Table 1. *F1 and F2 values for 10 interval end points of /ɑ̃/ (Hz)*

Interval End Points	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
F1	531	637	676	690	640	557	461	414	386	372
F2	1315	1185	1122	1119	1121	1108	1106	1150	1223	1441

Step 2. Calculate the difference between each interval end point for F1 and F2

The increase/decrease value (difference value) at each interval end point is calculated resulting in 9 values extracted using the nasal vowel /ɑ̃/ as shown in Table 2.

Table 2. *Difference values between two interval end points of /ɑ̃/ (Hz)*

Difference Values	20-10%	30-20%	40-30%	50-40%	60-50%	70-60%	80-70%	90-80%	100-90%
F1	106	39	14	-50	-83	-96	-47	-28	-14
F2	-129	-63	-3	2	-13	-2	44	72	218

Step 3. Identify stable sections using the difference thresholds of F1 and F2

The stable sections of a vowel are identified as being the sections in which the difference between the interval end points (increase or decrease) is less than 60 Hz in F1 and less than 200 Hz in F2.

In Table 3, each interval section that is identified as being stable in terms of F1 or F2 is highlighted in light blue. Among these sections, the sections surrounded by the solid blue line indicate those sections in which both F1 and F2 fall within the stable difference thresholds which are the interval sections 20% to 50% and 70% to 90%. These sections are identified as the stable sections of the nasal vowel /ɑ̃/.

Table 3. *Stable sections determined based on the difference threshold for the 9 intervals of /ɑ̃/ (Hz)*

Stable Sections	20-10%	30-20%	40-30%	50-40%	60-50%	70-60%	80-70%	90-80%	100-90%
F1	106	39	14	-50	-83	-96	-47	-28	-14
F2	-129	-63	-3	2	-13	-2	44	72	218

4. Results

4.1. Stable Sections of French Nasal Vowels /ɛ̃, ɑ̃, ɔ̃/

Table 4 presents the extracted stable sections of nasal vowels based on the study. The stable sections are indicated by the sections surrounded by the solid blue line which covers sections ranging from 20% to 50%. In all three nasal vowels, the stable section of F2 is approximately twice as long as that of F1.

Table 4. *Stable section of nasal vowels: 20%~50%*

Nasal Vowels		20-10%	30-20%	40-30%	50-40%	60-50%	70-60%	80-70%	90-80%	100-90%
/ɑ̃/	F1	106	39	14	-50	-83	-96	-47	-28	-14
	F2	-129	-63	-3	2	-13	-2	44	72	218
/ɛ̃/	F1	147	38	-1	-26	-59	-111	-101	-109	-37
	F2	-118	-100	-98	-84	-17	-85	14	-58	0
/ɔ̃/	F1	92	28	-22	-26	-83	-41	-65	-36	-2
	F2	-137	44	68	7	3	18	1	48	61

4.2. Stable Sections of French Oral Vowels /ɛ, a, ɔ/

In Table 5, the stable sections of the corresponding oral vowels are shown as the sections surrounded by the solid blue line which range from 20% to 80%. For /a/ and /ɛ/, the incremental values for both F1 and F2 fall within the stable difference thresholds, and the number of stable intervals is the same.

Table 5. *Stable sections of corresponding oral vowels: 20%~80%*

Oral Vowels		20-10%	30-20%	40-30%	50-40%	60-50%	70-60%	80-70%	90-80%	100-90%
/a/	F1	59	38	36	30	41	22	11	62	24
	F2	-93	-66	-52	-39	35	61	93	247	75
/ɛ/	F1	109	60	35	15	-9	1	32	37	33
	F2	-84	-76	-43	-70	-53	-17	-13	32	13
/ɔ/	F1	22	22	41	20	-24	-28	-30	-79	-51
	F2	-89	-65	23	-6	8	56	47	9	96

For all three corresponding oral vowels, the stable sections were between 20% to 80%, and between 90% to 100%. The stable sections of /a/ and /ɔ/ were between 10% to 80% and between 90% to 100%, while the stable sections of /ɛ/ were between 20% and 100%. In this study, boundary sections located at both extremes of 0% to 10% and 90% to 100% are not considered, and sections with F1 and F2 values consecutively below the stable difference thresholds were identified. Therefore, the stable sections of the oral counterparts are the sections between 20% to 80%.

4.3. Comparison of F1 and F2 Extracted from Stable Sections and from Midpoints

Figure 2 displays a spatial graph for the three nasal vowels /ɑ̃/, /ɛ̃/, and /ɔ̃/, with the formant frequency values at the midpoint represented by a dotted line and the stable section represented by a solid line.

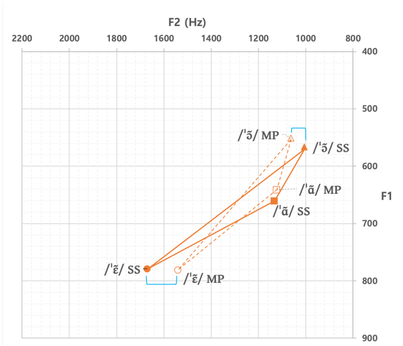

Figure 2. *Vowel space area of midpoint values (MP) and stable section values (SS): Nasal vowels*

Table 6 indicates that there is no significant difference in F1 of the three nasal vowels when comparing the midpoint values and stable section values. Thus, it is difficult to observe any significant difference in the formant frequency value associated with the size of the aperture, regardless of the calculation method used. However, a significant difference in F2 values can be observed between the two calculation methods for /ɛ̃/ and /ɔ̃/. For /ɛ̃/, the F2 value of the stable section was 128.9Hz higher than that of the midpoint, whereas, for /ɔ̃/, the F2 value of the midpoint was 58Hz higher than that of the stable section.

Table 6. *Difference between the midpoint values and the stable section values for each nasal vowel*

Nasal Vowels		/ɑ̃/ MP	/ɑ̃/ SS	/ɛ̃/ MP	/ɛ̃/ SS	/ɔ̃/ MP	/ɔ̃/ SS
F1	N	87	86	58	60	85	80
	M (SD)	641.1 (172.3)	660.5 (99.6)	781.3 (104.9)	779.0 (86.3)	551.8 (144.3)	567.1 (100.9)

	$t(p)$	-0.910(0.365)		0.131(0.896)		-0.794(0.429)	
F2	M (SD)	1123.8 (210.4)	1132.8 (111.4)	1541.7 (275.8)	1670.7 (168.2)	1062.8 (165.5)	1004.8 (114.7)
	$t(p)$	-0.353(0.724)		-3.054(0.003)**		2.629(0.009)**	

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Based on a calculation of the vowel space area using the arithmetic formula of [47], the stable section value (1.75kHz^2) represented a wider vowel space than the midpoint value (1.44kHz^2) by 0.31kHz^2. This difference in the area can be considered to be significant, with the value being approximately twice as large as that of the oral vowels (0.14kHz^2). When the interval of coarticulation with the preceding consonant is short, as in the case of the stable section, vowel centralization is reduced, resulting in a wider vowel space [4]. On the other hand, in the case of the midpoint, vowel variation is more pronounced, causing the vowel space to narrow and become more centralized.

Figure 3 shows the formant frequency values at the midpoint (dotted line) and the stable section of 20% to 80% (solid line) for the three oral vowels /a/, /ɛ/, and /ɔ/, represented by a spatial graph.

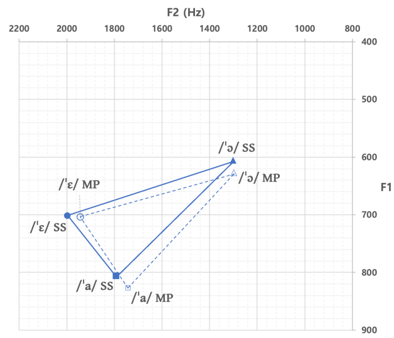

Figure 3. *Vowel space area of midpoint values (MP) and stable section values (SS): Oral vowels*

The statistical analysis shows that the difference between the midpoint values and the stable section values of the three oral vowels is not significant. Examining this difference in terms of vowel space, it is shown that the midpoint value (4.76kHz^2) is larger than the stable section value (4.62kHz^2) by 0.14kHz^2. However, it is difficult to determine that this difference is significant as difference based on the location of the vowel is not statistically significant.

Table 7. D*ifference between the midpoint values and the stable section values for each oral vowel*

Oral Vowels		/a/ MP	/a/ SS	/ɛ/ MP	/ɛ/ SS	/ɔ/ MP	/ɔ/ SS
F1	N	101	101	68	68	80	80
	M (SD)	829.9 (111.2)	806.4 (89.5)	703.6 (92.4)	701.6 (83.4)	627.3 (73.5)	605.9 (76.1)
	$t(p)$	1.449(0.149)		0.129(0.897)		1.807(0.073)	
F2	M (SD)	1742.5 (370.5)	1792.4 (249.6)	1943.5 (476.1)	1996.9 (245.1)	1296.9(152.6)	1301.2 (137.2)
	$t(p)$	-1.124(0.263)		-0.823(0.412)		-.0185(0.854)	

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

5. Conclusions

This study identified a stable section in French nasal vowels, which are known for their complex formant structure, based on the difference thresholds of F1 and F2 reported in [44, 45]. Based on the results of the study, the stable sections of nasal vowels were identified as being the sections between 20% to 50%. The distribution of the stable sections is biased towards the left side when viewed from the midpoint, which may be due to the anti-formant sections, as vocal energy flows not only to the oral cavity but also to the nasal cavity. The stable sections of F2 for the three nasal vowels were found to be approximately twice as long as that of F1. On the other hand, the stable sections of the oral counterparts were identified as being the sections between 20% to 80%. This was a result consistent with previous studies. Finally, as a result of comparing the midpoint and stable section values, especially in nasal vowels, there was a significant difference in vowels /ɛ̃/ and /ɔ̃/ for F2, but not for F1. Thus, the stable section represents a wider vowel space than the midpoint.

Extracting formant frequency values at the midpoint for French nasal vowels can be unreliable because the anti-formant section does not provide all of the relevant acoustic information. To address this issue, this study identified a stable section where the difference values of each of the nine intervals were below 60 Hz for F1 and 200 Hz for F2. The stable section for nasal vowels was found to be between the 20% to 50% interval sections with a midpoint of 35%, and for oral counterparts, it was between the 20% to 80% interval sections with a midpoint of 50%. Based on the fact that the results of the oral vowels are in agreement with the previous studies, the results for nasal vowels can also be regarded as reasonable. This is expected to be useful in extracting formant frequency values of nasal vowels in future studies. However, the fact that the data in this study was based on read speech produced by a single speaker limits the generalizability of our findings. Future research should incorporate spontaneous speech and a corpus of multiple speakers to enhance our understanding of the stable sections of French nasal and oral vowels.

6. Acknowledgments

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2022-2018-0-01833) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation).

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