The Effect of Surprisal on Articulatory Gestures in Polish Consonant-to-Vowel Transitions: A Pilot EMA Study

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Abstract

This study is concerned with the relation between the information-theoretic notion of surprisal and articulatory gesture in Polish consonant-to-vowel transitions. It addresses the question of the influence of diphone predictability on spectral trajectories and articulatory gestures by relating the effect of surprisal with motor fluency. The study combines the computation of locus equations (LE) with kinematic data obtained from electromagnetic articulograph (EMA). The kinematic and acoustic data showed that a small coarticulation effect was present in the high- and low-surprisal clusters. Regardless of some small discrepancies across the measures, a high degree of overlap of adjacent segments is reported for the mid-surprisal group in both domains. Two explanations of the observed effect are proposed. The first refers to low-surprisal coarticulation resistance and suggests the need to disambiguate predictable sequences. The second, observed in high surprisal clusters, refers to the prominence given to emphasize the unexpected concatenation.

1 Introduction

The relation between information density and phonetic encoding is reciprocal: the more surprising the information, the more prominent the encoding. Speech production patterns on the acoustic and articulatory planes are influenced by information structure and vary depending on the distribution of information conveyed by the message [1, 2]. This phenomenon finds its explanation in efficient communication principles, where easily predictable and contextually enhanced elements are prone to reductions, higher degrees of coarticulation, or even omission. On the other hand, a more unexpected focus with less predictable content often requires acoustic prominence, emphasis, or even reduplication [3, 4].

In this work, we address the relation between predictability and reduction in Polish CV groups on the articulatory and acoustic levels. We relate the information-theoretic measure of contextual unpredictability, i.e., surprisal with coarticulation strength and attempt to understand how the predictability of vocalic segments corresponds with articulatory gestures and CV transitions in meaningless diphones. Since the influence of contextual probability on speech production has already been discovered on the morphophonological level [5, 6], the focus on such a highly constrained unit requires further justification in larger kinematic corpora, such as EMA-AME [7], MOCHA-TIMIT [8], DoubleTalk [9] and MNGU0 [10]. To address the counter-intuitive question of the 'informativity of meaningless', we try to determine whether speech production is inherently constrained by the high surprisal effect, even with the absence of semantics on the diphone level, which results in a low degree of coarticulation; or, conversely, whether the effect of articulatory and acoustic prominence given to disambiguate highly-predictable, low-surprisal sequences occurs and results in reverse patterns of coarticulation resistance. In other words, we assume that certain units with various information load and contextually determined frequency of occurrence require different processing effort, which results in distinctive phonetic encoding.

We concentrate on the diphone level to examine the role of surprisal in the highly limited and phonetically constrained environment of Polish CV sequences. In line with the probabilistic reduction hypothesis [1, 2, 11], we attempt to find a relation between segment unexpectedness and its acoustic and articulatory encoding, even in an experimental setup which is highly divergent from the natural speech environment.

1.1 Aims and hypothesis

The main goal of this paper is to test the effect of surprisal on the articulatory gestures of Polish CV groups, composed of voiceless velar plosives and monophthongs, using acoustic and kinematic data. We attempt to present the influence of surprisal on articulatory gestures and F2 dynamics with a focus on consonant-to-vowel transitions.

We assume that higher diphone surprisal values correspond to lower coarticulation strengths, whereas contextually predictable segments with lower surprisal values are produced with higher degrees of coarticulation. This premise relates to the applied measures in the dependency relation, that is: the lower the surprisal, the steeper the LE regression slopes of F2 measured at vowel onset and midpoint, and vice versa.

1.2 Related work

The relation of information density and phonetic encoding was previously investigated by [1, 3] who concluded that information-theoretic factors have an influence on phonetic encoding on various levels of representation, from segmental to suprasegmental [4]. Similarly to our study, the anticipatory coarticulation in CV syllables was investigated by [12, 13] with the application of the EMA methodology. While the acoustic and kinematic data do not always correspond to each other in a linear fashion [14, 15], many previous studies justify the approach of combining the articulatory and acoustics measures in the analyses of articulatory gestures [16, 17]. Even though in this investigation we recorded only one subject, a survey of 905 EMA studies [18] reports that one-participant experiments, perhaps due to fatigue of data collection, are not uncommon.

The relation between F2 and the horizontal consonant-to-vowel gesture from the release to the vowel midpoint can be captured by Locus Equations. Since the introduction of LEs in the 60s [19] the method of presenting formant transitions on the basis of two time stamps has been widely applied in estimating vowel reduction [20], categorization of the place of occlusion [21, 22], degree of coarticulation [15, 23], expression of the articulatory synergy [24], and more recently, has provided an insight into the articulation of CV groups in conjunction with articulographic data [12, 13].

The information-theoretic notion of surprisal that corresponds to unit predictability in a given context was proposed by [25]. The introduced notion of surprisal allows us to calculate the contextual unit probability on various linguistic levels. With respect to the focus of our study, we refer to the unexpectedness of CV sequences on the basis of data extracted from spoken corpora, similarly to [6]. The influence of surprisal on the articulatory patterns in CV contexts can be treated as a modifier of motor fluency, which was already pointed out by [6, 26]. In parallel to coarticulation understood as a gestural and spectral overlap of adjacent segments, a related concept, 'coarticulation resistance', was introduced by [17] and defined as the degree of articulatory variability of consonants or vowels as a function of their phonetic context. As pointed out by [27], the correspondence of LE slopes with coarticulation resistance can be explained by the DAC (Degree of Articulatory Constraint) model [28]. By analogy to the above-mentioned studies, we attempt to specify contextual constraints, and focus on the predictability of diphone segments by implementing a measure of surprisal.

2 Material and measurements

The CV sequences consisted of a voiceless velar stop and one from the set of Polish monophthongs: /k/ + /a, ɛ, i, ɔ, u, ɨ/. None of the monophthongs in Polish have a phonological length distinction, so the influence of segment duration was excluded from the potential set of distractors. To account for the influence of VOT (Voice onset time), only one stop was tested due to the potential uncontrolled effect caused by obstruents with various long-lags, which show a tendency for steeper LE slopes when F2 onset coincides with the first glottal pulse [29]. The CV sequences were clustered into three groups depending on the surprisal. The surprisal values were calculated on the basis of the conditional probabilities of the above-mentioned vowels following the voiceless velar stop in the spoken NKJP (The National Corpus of Polish) database [30] using the formula $-log_2 P(V|k)$, in which V corresponds to one of the six Polish monophthongs that could follow the consonant /k/. The result of the negative log (base 2) transformation on the conditional probability yields a measure of the unexpectedness of a vowel token in a CV context, rendered in bits. Then, the CV sequences were clustered into three surprisal-based groups. The high surprisal group was comprised of /kɛ/ and /kɨ/, the mid-surprisal group contained /ki/ and /kɔ/; and the low surprisal sequences were/ku/ and /ka/. The recording sessions consisted of three parts: an accommodation stage to allow the speaker to get used to speaking with the EMA electrodes and wires [31], then self-paced uttering of vowels in isolation, and finally the uttering of the CV groups. To account for the influence of speech rate on coarticulation patterns [32], the subject was asked to maintain a comfortable tempo and to utter the sequences as effortlessly as possible. To cross-check the calibration procedure, a simple real-time orientation was conducted to ensure that reference (6 DOF) sensors show a relatively large Y value, and that the tongue tip (TT) sensor had a larger X value than the tongue back (TB) sensor. After the recording stage, the V and CV sequences were automatically segmented with minor manual boundary corrections, and the Euclidean distance (ED), that is, the square root of summed squared differences between the TB coil in the V onset and the midpoint position, was calculated.

2.1 Acoustic measurements

Acoustic data were collected simultaneously with the kinematic data and synchronised. The mono sound was recorded with a sampling rate of 48 kHz to uncompressed .wav format. The F2 data was extracted using the LPC Burg algorithm with window length = $0.025s$; maximum F2 threshold = 5000 Hz; dynamic range = 30 dB and preemphasis filter from 50 Hz. The F2 values from vowel onset and midpoint were then used to derive the LEs for the respective CV groups. The LEs were represented as linear slope–intercept regressions of the F2 onset frequency transition to the F2 frequency in the middle of the vowels. After the F2 values were extracted, the LEs were computed to define the degree of coarticulation in the CV groups, according to the equation $F2_o = k \times F2_m + c$, in which $F2_o$ refers to second formant value at the vowel onset; $F2_m$ = F2 at the vowel midpoint; k = slope, which indicates the degree of change of F2 across two measuring points; and c = intercept. In order to obtain and extract these data, two 12-minute long recording sessions were conducted. The data from the first recording session were discarded due to technical difficulties and another session was recorded.

2.2 Articulatory measurements

Articulatory data were gathered by means of NDI Wave Articulograph with a 100 Hz sampling rate. Before the recording, the autocalibration was run to meet the standard accuracy of < 0.5 mm in the near (300 mm^3) acquisition field [33]. The naïve subject was a male native speaker of Polish with no non-standard dialectal background, and without hearing, speech, or language disorders. In total, 649 vowels in isolation and 693 vowels proceeded by voiceless velar stops were recorded from this speaker. To capture the articulatory gesture, three sensors were attached to the midsagittal plane of the tongue. The tongue tip (TT) sensor was placed 1 cm from the anatomical apex. The tongue back (TB) sensor was placed at a comfortable distance of 4 cm from the TT, and the tongue middle (TM) sensor was attached at the midpoint between the TT and TB, that is, 2 cm behind the TT coil. The two-channel six degrees of freedom (6 DOF) reference coils were attached to the left mastoid bone and nasion for head and skin movement normalization. The sensors were covered with liquid latex beforehand and glued to the dried tongue with nontoxic dental adhesive. One sensor was placed at the lower incisors for tracking the movements of the jaw. The occlusal plane was recorded with coils attached to the protractor. The palatal probe was done before the recording session, and after the recommended accommodation stage with 6D palate trace sensor. Data from one recording session was discarded due to sensor displacement. Afterwards, the tongue was dried again for the coil attachment and the entire session was repeated to ensure the measurement and reference consistency.

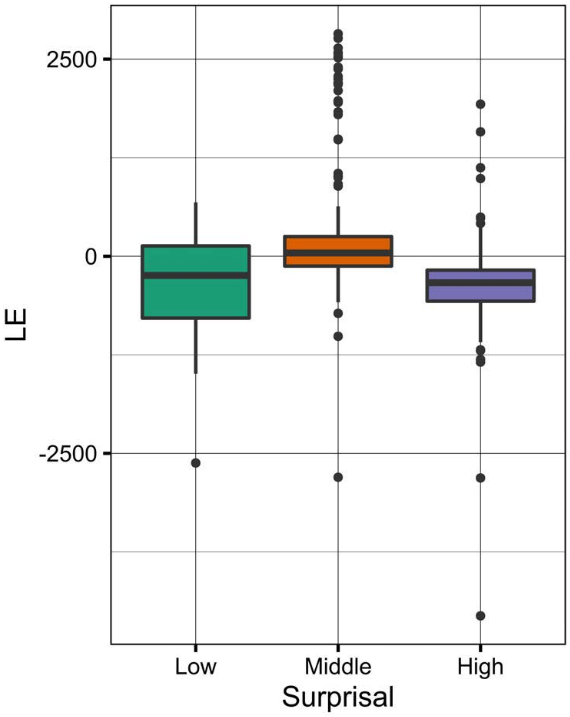

Figure 1: LE slopes across three groups of surprisal. Low LE correspond to low coarticulation.

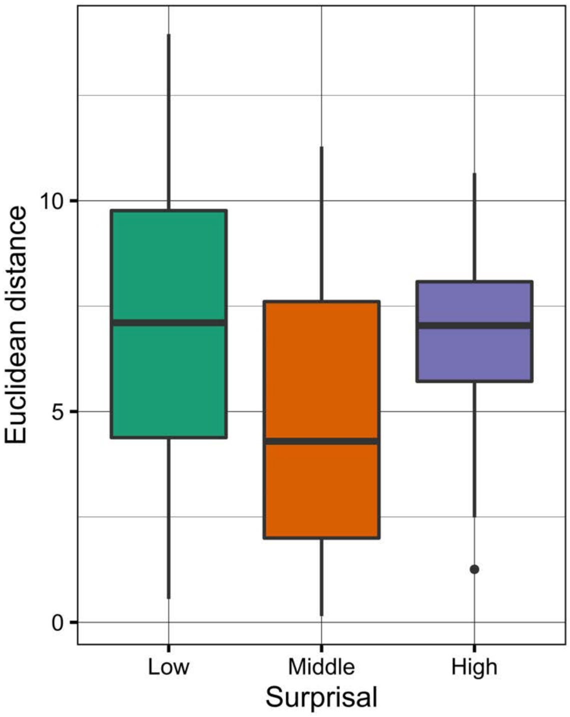

Figure 2: ED [in mm] across three groups of surprisal. High ED correspond to low coarticulation.

3 Results

Less than 1% of the kinematic data, including sensor position and rotation in quaternion 4-D unit vector, were discarded due to missing sensor input. The corresponding acoustic data points were discarded from the analysis. The descriptive statistics, along with the Kolmogorov-Smirnov test were calculated for the dependent variables with the FSA package [34] in R [35]. Then, the Kruskal-Wallis test and the post-hoc Dunn's test with Holm's correction for multiple comparisons were performed.

The results of the Kolmogorov-Smirnov test showed significant deviance from normal distribution of five tested variables across the surprisal groups, that is: in the low surprisal cluster (LE: $D = 0.13, p < 0.001$, ED: $D = 0.11, p < 0.001$); the mid-surprisal (LE: $D = 0.26, p < 0.001$, ED: $D = 0.14, p < 0.001$); and the high surprisal (LE: $D = 0.12, p < 0.001$, ED: $D = 0.04, p = 0.200$). Therefore, the Kruskal-Wallis test was conducted to assess the differences in ED and LE between the surprisal groups.

A steep slope across tokens indicates maximal coarticulation and corresponds to small differences between the F2 at onset and midpoint with a high overlap of the segments. In contrast, a shallow slope corresponds to a low coarticulation effect and minimal overlap of the adjacent segments. On the basis of the gathered acoustic data, a strong effect of the surprisal group on the LE slopes was discovered ($H(2) = 138.71, p < 0.001, \epsilon^2 = 0.20$). The post-hoc tests showed higher coarticulation for the middle surprisal groups, compared with low surprisal ($Z = 11.13, p < 0.001$) as well as high surprisal ($Z = -8.87, p < 0.001$). Additionally, the low surprisal group had steeper slopes than the high surprisal clusters ($Z = -2.23, p = 0.020$), see Figure 1.

The Euclidean distance between the position of the TB electrode measured at the two timestamps reflects the articulation resistance in relation: the larger the distance, the lower the degree of coarticulation. The analyzed set of kinematic data showed a similar correspondence to the one discovered on the basis of the acoustic data but with moderate magnitude ($H(2) = 83.268, p < 0.001, \epsilon^2 = 0.12$). The post-hoc test showed a higher coarticulation for the middle surprisal groups compared with low surprisal ($Z = -8.05, p < 0.001$), as well as high surprisal groups ($Z = -7.67, p < 0.001$). In the kinematic dataset, no significant differences were observed between the surprisal boundary groups ($Z = 0.36, p < 0.717$), see Figure 2.

4 Discussion

In this research, we aimed to estimate the degree of coarticulation on the level of the diphone CV transition. We expected to discover an effect of the unexpectedness of a segment on the articulatory gesture of a highly constrained cluster. Since the coarticulation strength cannot be inferred from the formant values only, we applied a hybrid methodology and combined spectral measures with the kinematic data. On the basis of measurements from two different domains, we concluded that the degree of coarticulation of the Polish CV groups is the highest in the middle surprisal cluster, whereas the low and high surprisal groups are characterized by higher coarticulation resistance and lower spectral overlap. Hence, our initial expectations were confirmed only in part.

Possibly due to limited size of the recorded data, we also observed discrepancies between the acoustic signal and its kinematic source. Even though a linear correspondence was not discovered, the patterns are consistent across the domains, which complements the argument that the LE measure does not necessarily reflect the motor functioning of the articulator [15, 16]. Furthermore, formants are influenced by too many factors to obtain a clear TB sensor position and F2 fluctuation. Hence, one of the reasons for why the tendencies across the domains are approximated rather than ideal can be traced to the positioning of the TB coil on the tongue. We assume that more posterior placement might contribute to higher correlation between the acoustic and kinematic data measured on the basis of the second formant value and the TB sensor position.

In the spectral domain, the minor differences between the F2 measures also seem to support the CV synchrony hypothesis. Furthermore, it should be noticed that the experimental setup itself can cause hyperarticulated speech [36], which in consequence can lead to certain reductions in articulatory gestures [37]. The experimental design with monotonous repetitions can also influence the degree of anticipatory coarticulation due to the increased effort of speaking in lab conditions with a bundle of wires. The diversity of the recording data can also strengthen the outcomes because of the possible influence of the competition effect of habituation, which refers to the effortless pattern of articulation in EMA. Such an experimental setup might involve gestures that diverge from the natural speech.

5 Conclusions

We assume that coarticulation measured on the diphone transition is a consequence of a twofold surprisal effect. Firstly, regarding the small degree of coarticulation in the low surprisal groups, it can be assumed that the behavioural pattern contributes to the need for segment disambiguation in the absence of the supportive context of surrounding meaningful elements. Secondly, the low coarticulation effect observed in the high surprisal sequences adheres to an underlying pattern of giving prominence in articulation to segmental concatenations with low predictability. In support of both explanations, the middle surprisal group showed the highest degree of coarticulation across the domains, hence neither the need for disambiguation nor the prominence effect was present in frequent phonotactic sequences. The observed effect can also be attributed to motor practice, which suggests an improvement of the articulatory skills with frequency of use [38, 39]. Motor practice is associated with a stronger overlap of two adjacent gestures and increases with the frequency of sequence occurrence. Increasing experience in motor practice can also lead to enhanced kinematic movements and more extreme articulation [40].

To further extend this study, a larger pool of participants would be desired. The increase of the sampling rate to 400 Hz can also bring higher resolution in the motion capture data. Regarding the information-theoretical approach, the further extension of this pilot study might involve, apart from surprisal, entropy as an index of competition in vowel selection.

Even though the aforementioned methodological issues should be addressed in further studies on the effect of surprisal on articulatory gestures, we discovered the interplay of information-theoretic and phonetic measures and therefore concluded that phonotactic predictability can induce changes to speech production patterns even on the highly constrained diphone level. Our results are consistent with previous studies investigating the relation between coarticulation strength and contextual predictability. Interestingly, we discovered that the relation between surprisal and phonetic encoding occurs even on the segmental level and affects meaningless syllables uttered in isolation. This evidence provides an argument for the inherent nature of a surprisal component in language production, and suggests that the phonotactic unexpectedness of a segment influences motor fluency.

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