



Frustration in the Pattern Formation of Polysyllabic Words

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A novel frustrated system is given for the analysis of $(m + 1)$ -syllabled vocal sounds for languages with the m -vowel system, where the varieties of vowels are assumed to be m ($m \geq 2$). The necessary and sufficient condition for observing the sound frustration is that the configuration of m vowels in an m -syllabled word has a preference for the “repulsive” type, in which there is no duplication of an identical vowel. For languages that meet this requirement, no $(m + 1)$ -syllabled word can in principle select the present type because at most m different vowels are available and consequently the duplicated use of an identical vowel is inevitable. For languages showing a preference for the “attractive” type, where an identical vowel aggregates in a word, there arises no such conflict. In this paper, we first elucidate for Arabic with $m = 3$ how to deal with the conflicting situation, where a statistical approach based on the chi-square testing is employed. In addition to the conventional three-vowel system, analyses are made also for Russian, where a polysyllabic word contains both a stressed and an indeterminate vowel. Through the statistical analyses the selection scheme for quadrisyllabic configurations is found to be strongly dependent on the parts of speech as well as the gender of nouns. In order to emphasize the relevance to the sound model of binary oppositions, analyzed results of Greek verbs are also given.

Keywords: vocabulary statistics, frustrated system, phonological complexity, spontaneous pattern selection, competing interaction

INTRODUCTION

Suppose a language with a three-vowel system where the string of two vowels in a disyllabic word has a strong preference for the AB-type configuration (assuming that vowels A and B are different from each other). For this language, it can be expected that the string of a trisyllabic word has a preference for the ABC-type configuration (assuming C different from A and B) in comparison with other four patterns, AAB, ABA, ABB, and AAA. In a two-vowel system, however, conflict arises in determining the most probable vowel configuration, because the selection of ABC is not in principle possible. The situation would become more complicate for quadrisyllabic words of a three-vowel language bearing a strong preference for the AB as well as the ABC configurations, because the realization of the pattern ABCD (assuming D different from other three) is impossible, and consequently a compromise among other 14 combinations is necessary. For instance, for a language with vowels, /u/, /a/, and /i/, six choices {ua, ui, au, ai, iu, ia} for AB and those {uai, uia, aui, aiu, iua, iau} for ABC are possible. For the quadrisyllabic words, however, one will find a compromise between ABAC, ABCA, and ABCB. It should be noted here that, according to the Shannon’s theory of information transmission [1], in order to reduce redundancy, sound configurations such as AB, ABC, as well as ABCD would be preferable. As a

matter of fact, such a conflicting situation had possibly been mentioned previously for the analysis of spin glasses (for details see Appendix A in Supplementary Material); it is said that since 1977 this situation due to the competing interactions among spins has been called frustration [2], in an exceptional borrowing from either psychology or psychiatry, where such situations as seen in the Bateson's theory of a double binding and the prisoner's dilemma in game theory were presented. Spin-glass-like systems have also been mentioned in cross-disciplinary areas of physics. In elucidating mechanisms that govern the Belousov–Zhabotinsky reaction, coupling among *three* chemical oscillators with synchronization in the interval of $2\pi/3$ rad (triphase synchronization) was demonstrated, as a result of a compromise for minimizing effects due to the frustration [3]. In nonlinear optics, numerical simulations predicted that an intense laser beam propagating along a *three*-layered waveguide could show chaotic trajectories as if the guided optical wave were frustrated [4, 5]. Only recently has optical diffraction by a frustrated system been solved numerically for the triangular Ising antiferromagnet, a disordered lattice system consisting of two kinds of scatter and exhibiting geometric frustration [6]. In biophysics, in an attempt to construct a hexagonal lattice of repressing genes, so-called dynamical frustrated states have been found to appear, where the temporal evolution is chaotic, even if there is no built-in frustration [7]. In mathematical ecology, experimental results for a *three*-frogs system, in which a frog was joined into a pair calling out of phase, have been given [8]. Specifically, both the triphase and the 1:2 antiphase synchronization, including switching between the two states, have been reported. Here one might expect that a conflict similar to that observed for amphibians could be found as well for other animals that communicate with each other by means of sounds. It would be a matter of course that such an inference is valid also for the human being. More recently has the importance of the phenomenon been reviewed to illustrate how frustration is a fundamental concept in relating function to structural biology [9]. Besides the above research areas, the role of the phenomena termed link frustration has been emphasized in detailed analyses of phase-repulsive complex networks of oscillators interacting repressively [10–12]. Aside from these works concerning the frustration in the complex networks, go-ahead attempts to seek a point of contact between statistical physics and linguistics have been made so far, including applications and/or testing of the statistical laws that were previously predicted by Heap and Zipf [13–15] as well as graph-theoretical approaches to analyzing linguistic phenomena [16–18]. In parallel with these, continual efforts have been making to establish methodologies for quantitatively approaching to phonological complexity [19–22]. Of them, based on the notion of attraction and repulsion between phonemes, calculating cohesion and stability for phonological inventories in the UCLA Phonological Segment Inventory Database (UPSID) is of particular interest [19].

In this paper, a novel frustrated system is presented for the analysis of $(m + 1)$ -syllabled vocal sounds for languages with the m -vowel system, where the varieties of vowels are assumed to be m , an integer larger than unity. The necessary and sufficient condition for predicting the sound frustration

is that the configuration of m vowels in an m -syllabled word has a preference for the “repulsive” type, in which there is no duplication of an identical vowel. For languages that meet this requirement, $(m + 1)$ -syllabled words cannot permit of the present type because at most m different vowels are available and in consequence the duplicated use of an identical vowel is inevitable. Here a vowel per syllable is assumed. For languages showing a preference for the “attractive” type, a specific vowel aggregates in a word, and consequently there arises no frustration. Such arrangement of vowels is usually the case with non-European languages showing the vowel harmony, such as Mongolian, Turkish, Hungarian, Finnish, Telugu, and Ainu. Moreover, frustration would be distantly related in such languages as, for instance, Japanese [23], Indonesian, Malayan, and Polynesian, for which similar syllables are frequently reduplicated. Here one may notice that this method in constructing polysyllabic words is avoided in European languages, possibly because the reduplication reminds the speakers of infantile talk [24, 25]. For instance, in English there are disyllabic words such as “ticktack” and “zigzag,” each of which never became “tictick” and “zigzig.” (In Japanese these are realized as, respectively, *kati-kati* and *kune-kune*.) Although the reduplication will enhance redundancy, from the perspective of achieving reliable transmission of information, this scheme might not be necessarily regarded as disadvantageous. In what follows, how to cope with the conflicting situation is analyzed for Arabic with $m = 3$, where a statistical approach based on the chi-square testing is used. For systems under the sound frustration, no one can make an accurate estimation of the most frequent vowel configuration. In addition to the conventional *three*-vowel system, analyses are made for Russian, where a polysyllabic word contains both a stressed and an indeterminate vowel. Finally, in order to explore the relevance to the phonological theory based on the binary oppositions [26], analyzed results of Greek verbs are also given. Although the minimal form of meaning is not the word but the morpheme, below we shall concentrate on the former.

ANALYSIS AND DISCUSSION

According to a large-scale survey based on linguistic typology, the varieties of vowels in world's languages range from 3 to 14 [27]. Among these, most typical is the five-vowel system, which accounts for 32% [28]. For instance, major languages such as Spanish, Japanese, Swahili, Hausa, and Greek belong in this category [29]. However, to insist on the possibility of the frustration for the six-syllabled words, one must verify the fact that the “repulsive”-type configurations are selected in entire word systems including the two-, three-, four-, and five-syllabled ones. Note that, except technical terms, the vocabulary sizes of five- as well as six-syllabled words in common use are very limited, making impossible any statistical approach. This difficulty accompanying the most popular five-vowel system could be overcome by choosing a sample from a few minor languages with the two-vowel system. Unfortunately, if there were any in the past, all of them are nowadays either endangered

or dead, making their corpora unavailable. In addition, the classification of Kabardian and Abaza with a two-vowel language was judged to be questionable [27, 30, 31]. For this reason, below we would focus our attention on Arabic, which is known as a major language with the only *three* kinds of vowels, /u/, /a/, and /i/ [29], where discrimination between the short and the long vowels is not included. The three-vowel system would be responsible for establishing frustration in the quadrisyllabic sound system provided that one confirms that the “repulsive” configuration is selected both for the disyllabic and for the trisyllabic words. From surveyed results of words in corpora it has been found statistically that among the four parts of speech, which consist of nouns, verbs, adjectives, and adverbs, only adjectives bear the “repulsive” property; the results for disyllabic and trisyllabic words are shown in **Tables 1, 2**, respectively. Here results based on two corpora [32, 33] are compared, together with the expected values being obtainable analytically from the blending among the three kinds of vowels. First, we can find from **Table 1** that, irrespective of the size, *N*, of sampled words, the distribution of the two configurations, which are denoted by AB with the “repulsive” vowel arrangement and by AA with the “attractive” counterpart, gets highly distorted toward AB. To examine the statistical significance of the divergence from the expectation, we shall employ a hypothetical testing by means of the chi-square statistics [34]

$$\chi^2 = \sum(f_i - F_i)^2/F_i$$

where f_i and F_i , respectively, are the surveyed and the expected values; the summation extends over $i = 1$ to $i = j$; $j = 2, 5, \text{ and } 15$, respectively, for disyllabic, trisyllabic, and quadrisyllabic words. The corresponding chi-squared values will be attached to the foot of each table, where α in the bracket indicates the significant level for the statistical testing. For the two-dimensional correlation analysis (**Table 1**) the expected values can be calculated as

$$F_1 = s/2 - F_2 \quad \text{for AB,}$$

$$F_2 = (k^2 + m^2 + n^2)/(2s) \quad \text{for AA,}$$

with $s = k + m + n$, where k , m , and n , respectively, indicate the frequencies of /u/, /a/, and /i/. For the three-dimensional counterpart (**Table 2**) these values can be obtained with the formulae that were derived for the analysis of rhyming pattern selection in haiku [35].

Subsequently we shall focus our attention on **Table 2**, in which the results of the trisyllabic adjectives are seen. In contrast to the two patterns shown in **Table 1**, there are five choices. Of these, ABC (AAA) corresponds to the “repulsive” (“attractive”) type, while the remaining three, {AAB, ABA, ABB}, can be regarded as intermediate between the two extremes. It is evident from **Table 2** that independently of the corpus size *N* the distribution exhibits condensation in ABC, whereas rarefaction can be seen in AAA. From the results of **Tables 1, 2** it would be reasonable to conclude that the quadrisyllabic system of Arabic adjectives may be frustrated because of the strong tendency to have a preference for AB and ABC, as well as to avoid AA and AAA. The results for quadrisyllabic adjectives, which can be classified into the

TABLE 1 | Frequency distribution of the vowel configurations for disyllabic adjectives of Arabic, where *N* indicates the size of the vocabulary corpus [32, 33].

Configuration	(1) Yajima (<i>N</i> = 1500)		(2) Naiki (<i>N</i> = 6000)	
	Surveyed	Expected	Surveyed	Expected
AB	114	74.14	509	339.07
AA	17	56.86	54	223.93
Sum	131	131.00	563	563.00

The strings AB and AA symbolize, e.g., *ua* and *ii*, respectively. The distributions of the three vowels are (*u, a, i*) = (22, 136, 104) for (1), and (*u, a, i*) = (155, 552, 419) for (2).
 (1) $\chi^2 = 49.38$ ($\alpha = 4 \times 10^{-6}$).
 (2) $\chi^2 = 214.11$ ($\alpha = 2 \times 10^{-8}$).

TABLE 2 | Frequency distribution of the vowel configurations for trisyllabic adjectives of Arabic [32, 33].

Configuration	(1) Yajima (<i>N</i> = 1500)		(2) Naiki (<i>N</i> = 6000)	
	Surveyed	Expected	Surveyed	Expected
ABC	15	8.81	73	50.85
AAB	11	10.61	80	58.23
ABA	6	10.61	35	58.23
ABB	15	10.61	67	58.23
AAA	1	7.37	9	38.47
Sum	48	48.01	264	264.01

There are five choices possible, which can be grouped into three categories. Of them the first group {ABC} could be regarded as a ground state, whereas the second and the third ones correspond, respectively, to the first and the second excited states. Moreover the former consists of three-fold degenerate states {AAB, ABA, ABB}. The meanings of the strings are as **Table 1**. For instance, ABC symbolizes, e.g., *uai*. The distributions of the three vowels are (*u, a, i*) = (29, 70, 45) for (1), and (*u, a, i*) = (180, 377, 235) for (2).
 (1) $\chi^2 = 13.69$ ($\alpha = 8 \times 10^{-3}$).
 (2) $\chi^2 = 50.96$ ($\alpha = 3 \times 10^{-6}$).

15 patterns of vowel configurations, are given in **Table 3**. The formulae of the expected values, F_1 – F_{15} , are given in Appendix B in Supplementary Material. Note that, because in Arabic there are only three kinds of vowels available, the first pattern, #1:ABCD, is not possible. From **Table 3** one can summarize the results as follows:

- (1) There exist twin peaks for #3:ABAC (e.g., *'ajriyā' u* “brave”) and #14:ABBA (e.g., *thuqalā' u* “heavy”), together with twin local peaks for #2:AABC (e.g., *jabābiru* “gigantic”) and #5: ABBC (e.g., *muta'addid* “many”). Here the concentration on the pattern #3:ABAC could be explained by a point of compromise for avoiding the neighboring placement of an identical vowel. In other words, frustration is relieved by finding the compromise. However, the concentration on #14:ABBA probably connotes a linguistically profound reason, which makes impossible any explanation due to the avoiding effect. In order to discuss the linguistic reason why the two configurations are frequent, two samples, both of which are most typical of Arabic adjectives, are given:

barīʾ/ʾabriyāʾ u “innocent” → AB/#3:ABAC,
bakhīl/bukhalāʾ u “stingy” → AB/#14:ABBA.

Here the left and the right words off the slash indicate, respectively, the singular and its plural.

- (2) Contrary to a prediction, there is a dip on #4: ABCA.
- (3) The concentration on the configurations, #2:AABC to #7:ABCC, which reduce to a cluster with the three different vowels {A, B, C}, amounts to 56%, in contrast to 43% for other clusters, #8:AAAB to #14:ABBA, with two different vowels {A, B}.
- (4) Comparison between the surveyed and the expected values indicates that the avoidance for #15:AAAA (the completely “attractive” type) is worth notice.
- (5) Making a comparison between dual components in pairs such as (#2:AABC, #7:ABCC), (#3:ABAC, #6:ABCB), and (#9:AABA, #10:ABAA), one would conclude that in quadrisyllabic adjectives of Arabic an identical vowel tends to cohere rather on its beginning part. To the author’s knowledge, it seems that which type of cohesion to be selected depends on the history of each individual language. For the present three pairs, examples are given as follows:

#2: AABC *mayāmīnu* “lucky,”
 #7:ABCC *Kāthūlīkīy* “Catholic,”

#3:ABAC *ʾazkiyāʾu* “pure,”
 #6:ABCB *ʾūlāʾika* “those” *a.*,

#9:AABA *ʾijtimāʾīy* “social,”
 #10:ABAA *ʾIstarīnīy* “of English currency.”

It can be expected that if vowels of a language could be divided sharply into a fewer categories, frustration may occur in other languages. As a good example, here we take notice of Russian, the words of which are composed of *three* kinds of vowels. Namely, in addition to the accentual (*/á/, /é/, /í/, /ó/, /ú/, and /ì /·/*) as well as the accent-free vowels (*/a/, /e/, /o/, /ɪ/, /i/, and /u/*), they are often accompanied with an indeterminate vowel termed schwa */ə/* [37]. First of all, it should be noted that for at least the four parts of speech (i.e., nouns, verbs, adjectives, and adverbs) all the disyllabic words of Russian bear the feature of the “repulsive” type denoted with AB, e.g., *Bépa*[vʽɛrə] “belief”; consequently, duplicated use of vowels belonging to the same category is not allowed in a word [37]. For this reason, in order to show frustration in the quadrisyllabic system, analysis will be needed solely for the trisyllabic one. The results for the nouns are given in **Table 4**. Along with other Indo-European languages such as German, Romanian, and Bulgarian, there are *three* genders in Russian nouns, namely, the masculine, the neuter, and the feminine ones. We find from **Table 4** that, irrespective of the gender, trisyllabic Russian nouns exhibit the “repulsive” type, having a preference for the ABC arrangement (e.g., *пароход*[pəroxot] “steamship,” *озеро*[ozʽɪrə] “lake,” *фигура*[fʽɪgʽurə] “figure”); this is in contrast to the strong avoidance for the AAA type, bearing a remote resemblance to the Hund’s rule in quantum

TABLE 3 | Frequency distribution of the vowel configurations for quadrisyllabic adjectives of Arabic [32] (N = 6000).

No.	Configuration	Surveyed	Expected
#1	ABCD	0	0
#2	AABC	14	7.12
#3	ABAC	27	7.12
#4	ABCA	3	7.12
#5	ABBC	16	7.12
#6	ABCB	2	7.12
#7	ABCC	1	7.12
#8	AAAB	1	9.45
#9	AABA	7	9.45
#10	ABAA	2	9.45
#11	ABBB	2	9.45
#12	AABB	1	8.19
#13	ABAB	1	8.19
#14	ABBA	34	8.19
#15	AAAA	1	6.90
Sum		112	111.99

There are 15 choices, which can be grouped into five clusters. Among them the second group (#2:AABC-#7:ABCC) contains six-fold degenerate ground states, whereas the third to the fifth contain, respectively, four-fold degenerate excited states (#8:AAAB-#11:ABBB), three-fold degenerate excited ones (#12:AABB-#14:ABBA), and the most excited one (#15:AAAA). The meanings of the strings are as **Tables 1, 2**. For instance, ABAC signifies, e.g., *aiau*. The distribution of the three vowels is $(u, a, i) = (139, 212, 97)$. Note that in contrast with the former two cases (**Tables 1, 2**) the dominance between the vowels does not obey the general rule in accordance with which */u/* is least frequent [36]. $\chi^2 = 203.50$ ($\alpha = 10^{-10}$).

chemistry. Indeed, in **Table 4** there is no word allotted to the latter. The results for other parts of speech are shown in **Table 5**, where those of the verbs, the adjectives, and the adverbs are compared. Evidently, the feature of the distributions is very similar to those observed in the nouns (**Table 4**); an exception is seen solely in the surveyed frequency of the adjectives, for which surprising concentration on the pattern ABA (e.g., *короткий*[kərotkʽij] “short”; *богатый*[bagatʽij] “rich”) is seen. It should be stressed here that despite this abnormality the condition necessary for identifying the “repulsive” type, i.e., in addition to avoidance for AAA, a preference for ABC (e.g., *мировой*[mʽɪrovʽoj] “world” *a.*), is preserved along with the cases of the other two parts of speech. With the results of **Tables 4, 5** we could judge that the quadrisyllabic system of Russian vocables can be frustrated. On the basis of this judgment we finally consider quadrisyllabic words of this language. The results for the *three* nouns and for the other *three* parts of speech are given, respectively, in **Tables 6, 7**, from which we conclude as follows:

- (1) Because the number of syllables in a quadrisyllabic word exceeds that of the vowel categories, there is no frequency on #1: ABCD, corresponding to the perfectly “repulsive” type (**Tables 6, 7**).
- (2) Both for the neuter and for the feminine nouns, the surveyed distribution gets extremely distorted toward the group with the three different vowels (i.e., #2:AABC to #7:ABCC);

TABLE 4 | Frequency distribution of the vowel configurations for trisyllabic nouns of Russian [37].

Configuration	(a) Masculine		(b) Neuter		(c) Feminine	
	Surveyed	Expected	Surveyed	Expected	Surveyed	Expected
ABC	59	20.32	35	9.56	130	32.22
AAB	37	29.11	2	9.56	5	32.22
ABA	29	29.11	1	9.56	3	32.22
ABB	6	29.11	5	9.56	7	32.22
AAA	0	23.35	0	4.78	0	16.12
Sum	131	131.00	43	43.02	145	145.00

The distributions of the vowels are $(v_1, v_2, v_3) = (203, 131, 59)$ for (a), $(v_1, v_2, v_3) = (43, 43, 43)$ for (b), and $(v_1, v_2, v_3) = (147, 145, 143)$ for (c), where v_1, v_2 , and v_3 represent, respectively, the accent-free, the accentual, and the indeterminate vowels.

(a) $\chi^2 = 117.49$ ($\alpha = 2 \times 10^{-8}$).

(b) $\chi^2 = 88.34$ ($\alpha = 10^{-7}$).

(c) $\chi^2 = 382.16$ ($\alpha = 2 \times 10^{-11}$).

TABLE 5 | Frequency distribution of the vowel configurations for trisyllabic words of Russian [37].

Configuration	(a) Verb		(b) Adjective		(c) Adverb	
	Surveyed	Expected	Surveyed	Expected	Surveyed	Expected
ABC	212	70.27	37	16.72	58	19.04
AAB	82	79.11	8	44.67	8	20.89
ABA	39	79.11	129	44.67	18	20.89
ABB	23	79.11	27	44.67	10	20.89
AAA	0	48.40	0	50.28	0	12.30
Sum	356	356.00	201	201.01	94	94.01

The distributions of the vowels are $(v_1, v_2, v_3) = (475, 356, 237)$ for (a), $(v_1, v_2, v_3) = (360, 201, 42)$ for (b), and $(v_1, v_2, v_3) = (122, 94, 66)$ for (c).

(a) $\chi^2 = 394.48$ ($\alpha = 2 \times 10^{-11}$).

(b) $\chi^2 = 271.21$ ($\alpha = 2 \times 10^{-10}$).

(c) $\chi^2 = 106.08$ ($\alpha = 6 \times 10^{-8}$).

in particular, strong concentration is seen on #3: ABAC [Table 6(b),(c)], indicating that the frustration is relieved by preferentially selecting this configuration. To explain the reason why this pattern is most frequent, we shall put two samples typical of Russian:

внимание[vn'Ima'n'ijə] “attention” for neuter noun,

история[isto'r'ijə] “history” for feminine noun.

Evidently, both words are composed of a series of an accent-free, an accentual, an accent-free, and an indeterminate vowels, allowing them to belong to #3:ABAC.

- (3) In striking contrast to those of the two genders, the distribution of the masculine nouns becomes considerably broad; specifically, over #2:AABC to #10:ABAA its profile is found to be almost uniform. In other words, symmetry concerning the pattern selection is not broken and approximately maintained over the broad range [Table 6(a)]. Consequently, regarding the masculine nouns, relieving of frustration is *not* achieved!
- (4) In the distributions of the verbs and the adverbs, competition among #2:AABC, #3:ABAC, and #4:ABCA, which has occurred in the process of seeking for a compromise, can be observed [Table 7(a),(c)]. In other words, both parts of speech in the quadrisyllabic system select the above *three*

configurations from the “six-fold degenerate ground states” available. Therefore, one can conclude that for the two parts of speech the frustration is relieved *incompletely* among the three.

- (5) Again, a distinguished feature is seen in the behavior of the adjectives. Namely, a marked aggregation is found nowhere in the vicinity of #3:ABAC but is seen on #9:AABA (e.g., *нехороший*[n'ixaro'fij] “not good”) as well as #10:ABAA (e.g., *какой-нибудь*[kako:jn'ibut'] “certain”), the ratio of which amounts to 62% [Table 7(b)]. It appears that this property exhibits a good analogy with the population inversion of electrons in an atom.
- (6) In summary, how to deal with the matter of sound frustration varies substantially, depending both on the gender of nouns and on the parts of speech (Tables 6, 7). To conclude, with regard to the degree of reducing the frustration, one could decide ranking as follows: 1. Neuter nouns [Table 6 (b)]; 2. Feminine nouns [Table 6 (c)]; 3. Adverbs [Table 7 (c)]; 4. Adjectives [Table 7 (b)]; 5. Verbs [Table 7 (a)]; 6. Masculine nouns [Table 6 (a)].

Finally, we consider other classifications of the vowels. According to the spectral analyses based on an acoustic-engineering approach along with the auditory impression, Jakobson et al.

TABLE 6 | Frequency distribution of the vowel configurations for quadrisyllabic nouns of Russian [37] .

Configuration		(a) Masculine		(b) Neuter		(c) Feminine	
		Surveyed	Expected	Surveyed	Expected	Surveyed	Expected
#1	ABCD	0	0	0	0	0	0
#2	AABC	2	1.21	6	3.53	13	3.03
#3	ABAC	3	1.21	42	3.53	26	3.03
#4	ABCA	2	1.21	5	3.53	3	3.03
#5	ABBC	2	1.21	1	3.53	1	3.03
#6	ABCB	3	1.21	0	3.53	0	3.03
#7	ABCC	2	1.21	0	3.53	2	3.03
#8	AAAB	3	1.91	0	4.64	0	3.95
#9	AABA	3	1.91	0	4.64	0	3.95
#10	ABAA	1	1.91	1	4.64	2	3.95
#11	ABBB	0	1.91	0	4.64	0	3.95
#12	AABB	0	1.43	0	3.91	0	3.35
#13	ABAB	0	1.43	0	3.91	0	3.35
#14	ABBA	0	1.43	0	3.91	0	3.35
#15	AAAA	0	1.86	0	3.56	0	3.00
Sum		21	21.05	55	55.03	47	47.03

The distributions of the vowels are $(v_1, v_2, v_3) = (45, 21, 18)$ for (a), $(v_1, v_2, v_3) = (107, 55, 58)$ for (b), and $(v_1, v_2, v_3) = (91, 47, 50)$ for (c).
(a), (b), (c) χ^2 's are indeterminate.

TABLE 7 | Frequency distribution of the vowel configurations for quadrisyllabic words of Russian [37] .

Configuration		(a) Verb		(b) Adjective		(c) Adverb	
		Surveyed	Expected	Surveyed	Expected	Surveyed	Expected
#1	ABCD	0	0	0	0	0	0
#2	AABC	43	10.69	3	2.84	10	2.43
#3	ABAC	36	10.69	3	2.84	12	2.43
#4	ABCA	36	10.69	8	2.84	8	2.43
#5	ABBC	6	10.69	1	2.84	0	2.43
#6	ABCB	0	10.69	13	2.84	0	2.43
#7	ABCC	11	10.69	2	2.84	1	2.43
#8	AAAB	10	11.96	2	9.45	0	3.21
#9	AABA	6	11.96	30	9.45	3	3.21
#10	ABAA	0	11.96	24	9.45	4	3.21
#11	ABBB	5	11.96	1	9.45	0	3.21
#12	AABB	0	11.39	0	5.44	0	2.70
#13	ABAB	0	11.39	0	5.44	0	2.70
#14	ABBA	0	11.39	0	5.44	0	2.70
#15	AAAA	0	6.89	0	15.82	0	2.47
Sum		153	153.04	87	86.98	38	37.99

The distributions of the vowels are $(v_1, v_2, v_3) = (248, 153, 211)$ for (a), $(v_1, v_2, v_3) = (226, 87, 35)$ for (b), and $(v_1, v_2, v_3) = (74, 38, 40)$ for (c).
(a) $\chi^2 = 290.62$ ($\alpha = 4 \times 10^{-12}$).
(b) χ^2 is indeterminate.
(c) χ^2 is indeterminate.

TABLE 8 | Frequency distribution of the vowel configurations for disyllabic verbs of Modern Greek [39].

Configuration	(1) Opposition I		(2) Opposition II	
	Surveyed	Expected	Surveyed	Expected
AB	166	111.14	121	92.72
AA	40	94.86	85	113.28
Sum	206	206.00	206	206.00

The meanings of the strings AB and AA are as **Table 1**. The distributions of the five vowels are (u, o, a, e, i) = (10, 236, 39, 56, 71). With Opposition I (grave vs. acute) these are divided into the three categories, /u, o/, /a/, and /e, i/, while with Opposition II (compact vs. diffuse) they are divided into /a/, /o, e/, and /u, i/ [26]. Note that for Opposition I the string, e.g., ui, is classified in AB, whereas for Opposition II the same string is in AA.

(1) $\chi^2 = 58.81$ ($\alpha = 2 \times 10^{-6}$).

(2) $\chi^2 = 15.69$ ($\alpha = 3 \times 10^{-4}$).

TABLE 9 | Frequency distribution of the vowel configurations for trisyllabic verbs of Modern Greek [39].

Configuration	(1) Opposition I		(2) Opposition II	
	Surveyed	Expected	Surveyed	Expected
ABC	160	98.88	105	78.00
AAB	155	121.49	86	113.25
ABA	134	121.49	110	113.25
ABB	76	121.49	155	113.25
AAA	19	80.66	88	126.27
Sum	544	544.01	544	544.02

The meanings of the strings ABC to AAA are as **Table 2**. The distributions of the vowels are (u, o, a, e, i) = (46, 706, 304, 273, 303). Note that for Opposition I the string, e.g., iau, is classified in ABC, while for Opposition II the same string is in ABA.

(1) $\chi^2 = 112.48$ ($\alpha = 3 \times 10^{-8}$).

(2) $\chi^2 = 42.99$ ($\alpha = 8 \times 10^{-6}$).

[26] insisted that the distinctive features of all the phonemes in the world's languages can be described with the 12 binary oppositions. Their idea was established by the aid of the X-ray tomography of a speaker's palate and was responsible for a variety of phonological theories represented by the generative phonology [38]. Of the 12 oppositions, here we concentrate our attention on the following two cases: "grave vs. acute" (Opposition I) and "compact vs. diffuse" (Opposition II). In the former (Opposition I) the five vowels /u, o, a, e, i/ are classified into the grave /u, o/, the intermediate /a/, and the acute /e, i/ sounds; in terms of the classical phonetics, /u, o/, /a/, and /e, i/, respectively, coincide with the back, the centralized, and the front vowels in a palatogram. In the latter (Opposition II) the five vowels above are classified into the compact /a/, the intermediate /o, e/, and the diffuse /u, i/ sounds; conventionally, /a/ and /u, i/, respectively, correspond to the open and the close vowels. It should be noted here that with the use of these oppositions the complicate kinematics of a speaker's tongue in an oral cavity, which is linked together with the labial motion, can be reduced to the statistical distribution of the string configurations of the *three* categories. The results for the disyllabic and the trisyllabic verbs

TABLE 10 | Frequency distribution of the vowel configurations for quadrisyllabic verbs of Modern Greek [39].

Configuration	(1) Opposition I		(2) Opposition II	
	Surveyed	Expected	Surveyed	Expected
#1 ABCD	0	0	0	0
#2 AABC	71	30.87	41	25.67
#3 ABAC	52	30.87	19	25.67
#4 ABCA	33	30.87	39	25.67
#5 ABBC	32	30.87	10	25.67
#6 ABCB	30	30.87	20	25.67
#7 ABCC	26	30.87	44	25.67
#8 AAAB	55	36.20	29	41.64
#9 AABA	23	36.20	20	41.64
#10 ABAA	5	36.20	62	41.64
#11 ABBB	27	36.20	56	41.64
#12 AABB	45	34.21	61	30.39
#13 ABAB	33	34.21	14	30.39
#14 ABBA	12	34.21	17	30.39
#15 AAAA	10	21.35	22	42.23
Sum	454	454.00	454	453.98

The meanings of the strings #1-#15 are as **Table 3**. The distributions of the vowels are (u, o, a, e, i) = (33, 674, 415, 314, 380). Note that for Opposition I the string, e.g., eoia, is classified in #3:ABAC, while for Opposition II the same string is in #2:AABC.

(1) $\chi^2 = 135.32$ ($\alpha = 10^{-9}$).

(2) $\chi^2 = 126.97$ ($\alpha = 2 \times 10^{-9}$).

of Modern Greek [39] are shown in **Tables 8, 9**, respectively, where the first person singular and the present form of the verbs are implied (Note that in Modern Greek there is no indeterminate form). The vowel sounds of this language are listed in Appendix C in Supplementary Material. First we find that the qualitative features of the results in **Tables 8, 9** are identical to those given in the Arabic adjectives, **Tables 1, 2**, respectively. Namely, they show the strong tendency to have a preference for AB and ABC, as well as to avoid AA and AAA. Therefore, it would be reasonable to conclude that the quadrisyllabic system of the Greek verbs could be frustrated. Subsequently, the results for quadrisyllabic verbs (the first person, singular, and present form) of the same language are given in **Table 10**. Note that because the five vowels of Modern Greek are reduced to the *three* categories the first pattern #1: ABCD is not possible. From **Table 10** we find the following facts:

- (1) In both oppositions the avoidance for #15: AAAA is noticeable.
- (2) In Opposition I (grave vs. acute) the concentration on #2:AABC (e.g., αναγγέλλω "tell") as well as on #8:AAAB (e.g., αγανακτώ "get angry") is worthy of note, which is consistent with the preference for AAB in the trisyllabic counterpart [**Table 9**(1)].
- (3) In Opposition II (compact vs. diffuse) the concentration on #7: ABCC (e.g., αργιεύω "become violent"), #10:ABAA (e.g., αισθάνομαι "feel"), #11:ABBB (e.g., αποτελώ "form"), and #12:AABB (e.g., απαγγέλλω "recite") can be

seen, which is explainable by the preference for ABB in the trisyllabic counterpart [Table 9(2)].

- (4) In both oppositions it is particularly interesting to make a comparison between the *three* competing configurations, i.e., #3:ABAC, #4:ABCA, and #6:ABCB. For Opposition I frustration is reduced by selecting #3:ABAC (68%), whereas for Opposition II it is done by selecting #4:ABCA (52%), which would appear to compete also with #2:AABC. Here the percentage in the bracket stands for the relative difference between the surveyed and the expected frequencies.

CONCLUSION

With the use of a statistical approach it has been shown that sound frustration arises in quadrisyllabic vocables of Arabic, Russian, as well as Greek, and subsequently how to relieve the frustration has been discussed through comparison between the surveyed and the expected frequencies of the vowel configurations. It should be stressed again that the frustration presented in this paper would more or less be

inevitable for languages bearing in general the minimum redundancy (Notes added in Appendix D in Supplementary Material). The author believes that the results given here could provide a firm basis for finding frustrated systems in natural languages bearing more complicated vowel systems. To conclude, emphasis should be laid on the fact that the *three* frustrated systems presented above are quite unusual in that they are both spatial and temporal, depending on whether words are written with letters or realized with a voice.

AUTHOR CONTRIBUTIONS

This work has been made by KH.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <http://journal.frontiersin.org/article/10.3389/fphy.2016.00050/full#supplementary-material>

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