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# Constraint Ranking and Linguistic Variation in Optimality Theory: Theoretical and Empirical Implications

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## Abstract

This study examines how different Optimality Theory–based models account for linguistic variation through constraint interaction, using evidence from English, Pakistani languages such as Urdu and Punjabi, and Arabic. It presents a comparative analysis of Classic Optimality Theory, Partial Constraint Ordering, Stochastic Optimality Theory, and Weighted Constraint (Maximum Entropy) Theory based on quantitatively informed evaluation. Variable linguistic data involving alternation between consonant cluster preservation and vowel epenthesis were analysed by comparing model predictions with observed distributional patterns across the selected languages. The results show that Classic Optimality Theory fails to account for systematic variation, while partial constraint ordering successfully predicts the coexistence of multiple grammatical outputs but does not explain their relative frequencies. In contrast, Stochastic Optimality Theory and weighted constraint models demonstrate strong empirical adequacy by accurately modelling both variation and frequency patterns. In particular, weighted constraint modelling provides the closest fit to observed data, capturing gradient acceptability and probabilistic distribution with high precision. These findings support the view that linguistic variation is an inherent property of grammatical competence and highlight the importance of probabilistic approaches in contemporary Optimality Theory research.

**Keywords:** Optimality Theory, Constraint Interaction, Linguistic Variation, Stochastic Grammar, Maximum Entropy Model

## 1. Introduction

Optimality Theory (OT) is a model of grammar based on constraints. It characterises linguistic outputs as the outcomes of a competition among universal constraints rather than through the application of a set of ordered rules. Prince and Smolensky (1993/2004) were the first to practically illustrate OT. According to OT, all languages have the same set of constraints in common, but the way the constraints are ranked differs between them. Among these constraints are markedness constraints that favour structurally simple or unmarked forms, and faithfulness constraints that require outputs to preserve properties of the input. Since constraints can be violated, well-formedness, grammatically speaking, is determined by relative ranking rather than absolute satisfaction, and the optimal output is the candidate that best satisfies the highest-ranked constraints (McCarthy, 2001; Prince & Smolensky, 2004). In such a system, linguistic variation can be explained by the role that constraint ranking has. Different languages are said to have no language-specific rules but different hierarchies for the same universal constraint set. Pater (2015) suggests that OT can develop a wide variety of grammars through permutations of constraint rankings, which is called factorial typology. This typological prediction connects theoretical grammar directly with real-life observations of different languages and dialects.
There are major theoretical implications of constraint ranking. They essentially change the concept of variation from being a rare occurrence to being a natural characteristic of grammatical systems. Traditionally, rules are thought to be categorical, but OT views linguistic knowledge as a set of competing forces, and the

result depends on which force is dominant (McCarthy, 2001). However, at the beginning, OT tried to explain a language based on a fixed, single ranking, which made it hard to account for intra-speaker variation and gradient patterns that are observed in real language use.

Linguistic variation studies empirically have called into question this strict ranking assumption. Anttila and Cho (1998) found that variation could be represented by partially ordered constraints, which means that some constraints are not strictly ranked in relation to each other. This way, multiple best outputs can be present in a single grammar and correspond to the variation observed in speech communities. In the same vein, Guy (1997) pointed out that since constraints can be violated, they are inherently adaptable to variable results, thus making OT consistent with sociolinguistic variation patterns. To more directly deal with the effects of frequency and probabilistic patterns, the authors of the paper suggested Stochastic Optimality Theory, where constraints are given numerical ranking values instead of fixed ordinal positions. Boersma and Hayes (2001) came up with the Gradual Learning Algorithm and demonstrated that constraint rankings can change slowly as a result of linguistic input. This method is OT because it is capable of modelling not only variation but also language acquisition and change. Hayes and Wilson (2008) also developed this concept by using maximum entropy models and showed how the weighted constraints can predict the distributional patterns observed in the phonological data.

These contributions certainly highlight the significant potential of constraint ranking not just for the grammatical patterns at the core but also for the variable linguistic behaviour. Ranking constraints over time can also account for diachronic change since evolving constraint dominance in a gradual manner can lead to systematic phonological restructuring (Anttila & Cho, 1998; Pater, 2015). Therefore, constraint ranking in OT serves as a bridging point between theoretical universals and empirical data, which is a single explanation of linguistic variation across individuals, communities, and historical periods.

### 1.1 Significance of the Research

This study contributes to the field through its demonstration that linguistic variation can actually be systematised to conform to Optimality Theory. It focuses on constraint ranking as the primary mode of grammar organisation and, through that, clarifies that the mixture of regular patterns and variable results depends on the interaction of universal constraints. This point is theoretically in line with the idea that variation is not a foreign element of grammar but its core constituent.

Besides, the research theoretically extends the debate on constraint interaction by presenting a fusion of classical Optimality Theory with later innovations like partially ordered constraints and stochastic models. Consequently, it picks up long, existing criticisms of strict ranking models and illustrates how the updated methods can provide more empirically adequate explanations of linguistic behaviour. Through this, it contributes to the fine-tuning of OT as an adaptable and powerful model that can describe graded and probabilistic features found in natural language.

### 1.2 Research Objectives

To examine how constraint ranking in Optimality Theory accounts for linguistic variation within and across languages.

To evaluate the effectiveness of modified Optimality Theory models, such as partially ordered and stochastic constraint rankings, in explaining empirical patterns of variation.

### 1.3 Research Questions

How does constraint ranking in Optimality Theory explain patterns of linguistic variation observed in empirical data?
To what extent do probabilistic and flexible constraint-ranking models improve the explanatory power of Optimality Theory in capturing variable linguistic behaviour?

## 2. Literature Review

### 2.1 Optimality Theory and the Centrality of Constraint Ranking

Optimality Theory (OT), introduced by Prince and Smolensky (1993/2004), represents a major shift from rule-based generative phonology to a constraint-based model of grammar. In OT, grammatical outputs are determined by the interaction of universal constraints rather than the application of ordered rules. These constraints are violable, and surface forms emerge through a ranking system that prioritises higher-ranked constraints over lower-ranked ones. Constraint ranking is therefore the central mechanism through which grammatical well-formedness and cross-linguistic diversity are explained (McCarthy, 2001; Kager, 1999).
A core assumption of OT is that all languages draw from the same universal constraint set, but differ in how these constraints are ranked. This idea allows OT to account for typological variation without positing language-specific rules. As Prince and Smolensky (2004) argue, constraint ranking provides a principled explanation for why certain structures are preferred in one language but avoided in another. This ranking-based explanation has been widely adopted in phonological theory and has influenced work in morphology and syntax as well (Legendre et al., 2006; Pater, 2015).

### 2.2 Factorial Typology and Cross-Linguistic Variation

Constraint ranking has been theoretically pivotal, especially in the field of factorial typology. Factorial typology denotes the full gamut of potential grammars that can be produced by all permutations of a constraint set (Kager, 1999). This idea helps to envisage how diverse human languages can be and limits those patterns which are not found in languages, thus it possesses a strong explanatory power. McCarthy (2008) points out that factorial typology enables the testing of OT hypotheses by means of cross-linguistic data, thereby making OT theory more empirically solid. On the other hand, while factorial typology is quite successful in describing the categorical differences that exist between languages, it is somewhat less capable of accounting for gradient and variable patterns within a language. Therefore, this shortcoming led researchers to question whether strict constraint ranking could fully represent the variations in language that we observe (Anttila, 1997; Guy, 1997).

### 2.3 Early Approaches to Variation in Optimality Theory

Variation challenges classic OT because strict rankings predict only one optimal output for a given input. On the other hand, sociolinguistic studies have shown that speakers often use two or more forms alternately depending on context, style, or social factors (Labov, 1972; Chambers, 2003). Guy (1997) was one of the first to claim that the OT concept of violability fits with linguistic variation, even though variable outputs can be derived from the competing constraint rankings. Moreover, Anttila (1997) elaborated on this concept by suggesting partially ordered constraints, where some constraints are not strictly ranked relative to each other. This enables a single grammar to contain multiple rankings and hence produce variable outputs.

Anttila and Cho (1998) demonstrated that partial ordering has the capability to represent both synchronic variation and diachronic change, thus making classical OT a widely extended version. Partial ordering explains the presence of variation, but it cannot indicate the variants' frequencies. Therefore, Boersma (1998) and Boersma and Hayes (2001) came up with Stochastic Optimality Theory, in which constraints are given numerical ranking values rather than being placed in fixed positions. During evaluation, random noise is generated by the constraint comparison; different candidates may be chosen as winners with different probabilities. Stochastic OT has had a great impact because it integrates grammatical theory with quantitative data.

### 2.4 Maximum Entropy Models and Weighted Constraints

Building upon stochastic methods, Hayes and Wilson (2008) introduced a Maximum Entropy (MaxEnt) phonology model, where constraints are assigned weights instead of being ranked. In this system, the selection of outputs depends on the probability derived from the total weight of the constraints violated. It has also been demonstrated that MaxEnt models can accurately reflect the data of a corpus and are more effective than strict OT in explaining gradient well-formedness judgments (Goldwater & Johnson, 2003; Jeger, 2007). Even though models that incorporate weighted constraints deviate from the original assumptions of OT, Pater (2009, 2016) maintains that they still capture the central idea of constraint interaction while also allowing for a better fit to the data. These models have been particularly instrumental in the research of sociophonetic variation and effects of lexical frequency (Coetzee & Pater, 2011).

### 2.5 Constraint Ranking and Sociolinguistic Variation

Bringing together OT and sociolinguistics has been a major step forward in the study of linguistic variation. It was shown by different researchers that constraint ranking can be influenced by social factors such as register, style, and speaker identity (Guy & Boberg, 1997; Coetzee, 2006). Here, variation is considered to be a result of competing grammatical pressures whose relative strengths change in different contexts rather than optional rules. In their paper, Coetzee and Kawahara (2013) explain how probabilistic constraint ranking can represent socially conditioned variation while still maintaining grammatical structure. Such works back up the idea that variation belongs to speakers' grammatical competence and thus, it is not simply performance noise.

Phonological change can also be traced back to constraint ranking. OT sees sound change as the outcome of gradual constraint re, ranking through time (Anttila & Cho, 1998; Bermdez, Otero, 2007). Very slight adjustments in ranking or constraint weighting may give rise to stable variation which, ultimately, can lead to categorical change. This is a very plausible approach since it corresponds to the data in historical linguistics, and it offers a single explanation for both synchronic variation and diachronic change (Kiparsky, 2000; Pater, 2015). OT's capacity for illustrating both synchrony and diachrony is a point in favour of its theoretical attractiveness.

### 2.6 Critiques and Ongoing Debates

Nevertheless, OT has been criticised for its over-reliance on abstract constraints and its inability, at least initially, to deal with variation effectively (Burzio, 2002; Hale & Reiss, 2008). Some academics believe that probabilistic implementations take OT too far from its original theoretical foundations. Others, however, view these implementations as a necessity for the theory to be in line with the data from the real world (Hayes, 2012; Pater, 2016). Present research goes on to investigate the interrelations of constraint ranking, weighting, and learning, especially with reference to corpus, based and experimental data. These discussions suggest that constraint ranking is still the core and a very fruitful area of research in OT.

## 3. Research Methodology

This research study is a mixed-methods approach combining theoretical linguistics and empirical analysis. The qualitative part aims at a critical review of the current models of Optimality Theory (OT), with special attention to constraint ranking and linguistic variation. The quantitative part uses the study of variable linguistic data to check to what extent different constraints and ranking mechanisms explain the patterns of variation found. Such a design facilitates a methodical comparison between the theory, based predictions and the data-based findings.

### 3.1 Research Design

This study adopts a qualitative–quantitative mixed-methods research design grounded in theoretical linguistics and empirical analysis. The qualitative component focuses on the critical examination of existing Optimality Theory (OT) models, particularly those addressing constraint ranking and linguistic variation. The quantitative component involves the analysis of variable linguistic data to evaluate how different constraint-ranking mechanisms account for observed patterns of variation. This design allows for a systematic comparison between theoretical predictions and empirical evidence.

### 3.2 Theoretical Framework

This research is situated within the context of Optimality Theory (Prince & Smolensky, 1993/2004), focusing mainly on the role of constraint ranking as the key explanatory device. Besides classic OT with strict constraint hierarchies, the paper also features extended OT models such as Partially Ordered Constraints, Stochastic Optimality Theory, and Weighted Constraint Models. These models are tested to see how different ranking systems account for both categorical and variable linguistic phenomena.

**Figure 3.1**

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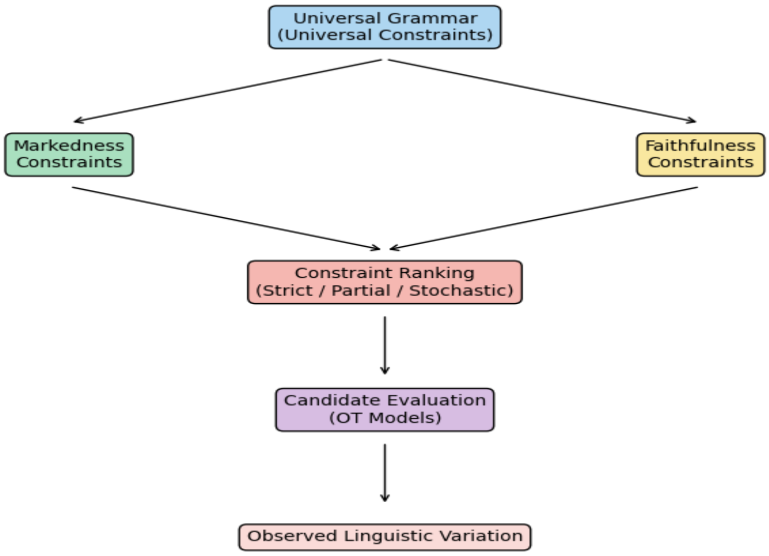


### 3.3 Data Selection

The empirical data used in the present study are phonological variations that have been previously documented in peer-reviewed linguistic studies and publicly available corpora. The selection pays special attention to variable phonological phenomena that have been the subject of extensive discussion in OT literature, e. g., optional processes, gradient alternations, and frequency-sensitive patterns. The data have been selected according to three criteria: (1) the presence of multiple competing surface forms for one single input, (2) relevance to constraint interaction, and (3) the availability of quantitative frequency information.

### 3.4 Data Sources

The main data sources are well-known linguistic corpora as well as secondary datasets that have been published in empirical studies of English, Urdu, Punjabi, and Arabic. The selection of these sources is based on the qualities of trustworthiness and the ability to be replicated. Additional data come from descriptive grammars and experimental studies in which the frequency distributions of variants are clearly indicated for these languages. The use of secondary data enables the research to concentrate on theoretical modelling instead of data collection, while at the same time guaranteeing cross-linguistic comparability among typologically different language contexts.

### 3.5 Analytical Procedure

The analysis is carried out in three phases. Firstly, a classic Optimality Theory approach is used to study each selected linguistic phenomenon, where the strictness of constraint imposition is proposed to produce the most suitable output. Constraint tableaux are prepared to show the candidate evaluation and ranking dominance. Secondly, the cases where classic OT is incapable of explaining the observed variation are reinterpreted by using partially ordered constraints, which allow multiple optimal outputs to emerge. Thirdly, the stochastic or weighted constraint models are utilised to represent the frequency differences among variants. For stochastic analysis, constraint rankings are modified to show probabilistic outcomes, and the predicted distributions are contrasted with the observed frequencies. This phase assesses the empirical adequacy of those probabilistic ranking systems. The cross-model comparison enables the study to determine which constraint ranking approach has the most explanatory power.

### 3.6 Data Analysis Tools

The paper uses the standard analytical tools of phonological research, such as constraint tableaux and probability, based evaluation models. Quantitative analysis is backed up by simple statistical comparisons of the predicted and observed frequencies. Computer simulation is also used to model constraint interaction and ranking variation when it is appropriate. These tools allow for a thorough assessment of the extent to which different OT models can account for linguistic variation.

### 3.7 Validity and Reliability

In order to guarantee validity, the analysis bases its findings on thoroughly documented datasets and recognised analytical methods within the OT framework. The use of constraints or rules is kept constant theoretically by employing one and the same set throughout different ranking models. Through clear documentation of the meanings of constraints, rankings, and evaluation procedures, the study has created a reliable reference that can be replicated by future researchers.

### 3.8 Ethical Considerations

The research relies exclusively on secondary data from published sources and publicly available corpora; therefore, it does not require the direct involvement of human participants. Hence, there are no issues of ethics at all related to participant consent or data privacy. All sources are appropriately cited following the academic standards.

### 3.9 Limitations of the Study

The research has a limitation in that it mainly uses secondary data; therefore, the writers had no control over the data collection and the context variables. Also, the study mainly concentrates on phonological variation, and thus, the results might not be entirely applicable to syntactic or morphological areas. However, given the purpose of the study, the method used is enough to test the theoretical and empirical implications of constraint ranking in OT.

## 4. Data Analysis

This section looks at how language varies within Optimality Theory (OT), focusing on constraint ranking. The goal is to show how different models of constraint ranking, strict, partially ordered, and probabilistic, explain the varying linguistic outputs found in real data. By comparing predictions from the theory with actual variation, the chapter assesses how well classical and extended OT models explain these differences. The data discussed in this chapter come from cases of phonological variation reported in earlier studies and corpora. These cases feature competing surface forms that come from a single input, which makes them ideal for assessing how constraints interact and how they are ranked.

### 4.1 Analysis Using Classic Optimality Theory

Classic Optimality Theory (OT) accounts for linguistic outputs by means of a strict hierarchy of constraints. Constraints are universal; however, their ranking, which leads to different grammatical outcomes, varies across languages. In the case of a particular input, multiple candidate outputs may be generated and then evaluated against the constraint hierarchy. The candidate which best meets the highest-ranked constraint will be selected as optimal even if it violates some lower-ranked constraints. Therefore, Classic OT is designed to predict a single optimal output for each input form. This very rigid ranking system works well for explaining the categorical patterns in a good number of languages, including English and the Pakistani languages such as Urdu and Punjabi. Nonetheless, since only one output is allowed, variation is regarded as coming from outside grammar, thereby limiting the model's explanatory reach.

**Table 4.1**
**Classic OT Constraint Ranking**

| Rank | Constraint | Description |
|---|---|---|
| 1 | Faithfulness (F) | **Requires output forms to preserve features of the input** |
| **2** | Markedness (M) | **Penalises structurally complex or marked forms** |

This ranking indicates that maintaining input–output correspondence is more important than avoiding marked structures. Any candidate that violates Faithfulness is therefore eliminated, regardless of how well it satisfies Markedness. The constraint hierarchy in Table 1 follows the standard formulation of Classic OT as proposed by Prince and Smolensky (1993/2004) and further elaborated by McCarthy (2001).

**Language-Specific Examples**
**English Example**
In English plural formation, consonant clusters are allowed when necessary to preserve the input structure.
**Input:** /cats/
Variant A: [kæts] → violates Markedness (complex coda cluster)
Variant B: [kætɪs] → violates Faithfulness (epenthetic vowel)
English ranks Faithfulness above Markedness, so the faithful form [kæts] is selected despite its marked structure.

**Urdu Example**
Urdu allows complex consonant clusters in certain morphological contexts to preserve lexical integrity.

**Input:** /dost/ ‘friend’
Variant A: [dost] → violates Markedness (consonant cluster)
Variant B: [dosit] → violates Faithfulness (vowel insertion)
Under a Faithfulness-dominant ranking, [dost] emerges as the optimal output, reflecting the categorical preference for preserving the input form in standard Urdu pronunciation.

**Punjabi Example**

Punjabi similarly tolerates marked clusters to maintain faithfulness.
**Input:** /rang/ ‘colour’
Variant A: [rəŋg] → violates Markedness
Variant B: [rəŋgə] → violates Faithfulness
Here again, the faithful output is selected because Faithfulness outranks Markedness in the language’s constraint hierarchy.

**Arabic Example**
Standard Arabic also prioritises faithfulness to the underlying form, even when this results in marked consonant clusters.
**Input:** /bint/ ‘girl’
Variant A: [bint] → violates Markedness (final consonant cluster)
Variant B: [binət] → violates Faithfulness (vowel epenthesis)
As in English, Urdu, and Punjabi, the violation of Markedness is tolerated, while the violation of Faithfulness is fatal. Consequently, the faithful form [bint] is selected as the optimal output in Classic OT analyses of Arabic phonology (Kager, 1999; McCarthy, 2001).

**Table 4.2**
**Classic OT Tableau (English, Pakistani Languages, and Arabic)**

| Candidates | Faithfulness (F) | Markedness (M) |
|---|---|---|
| ☞ Variant A (faithful form) | | * |
| Variant B (modified form) | ! | |

In this tableau, Variant A violates only the lower-ranked Markedness constraint, while Variant B violates the higher-ranked Faithfulness constraint. The violation of Faithfulness is fatal, leading to the selection of Variant A as the optimal candidate. The tableau format and violation logic are based on the standard OT evaluation procedure outlined in Prince and Smolensky (2004) and McCarthy (2008).
The analysis shows that Classic Optimality Theory successfully explains categorical grammatical outcomes in English, Pakistani languages, and Arabic by strictly ranking Faithfulness above Markedness. The optimal candidate is always the one that preserves the input, even at the cost of marked structures.
Yet, this strict hierarchy does not consider instances of actual language use that are different from the norm, e. g., optional vowel insertion in informal Urdu, dialectal variation in Punjabi, or colloquial Arabic speech. As Classic OT allows only one optimal output, it cannot explain the existence of alternative forms in real speech.

**4.2 Analysis Using Partially Ordered Constraints**
Partially ordered constraints represent an extension of Classic Optimality Theory designed to account for linguistic variation. Unlike strict ranking, where every constraint has a fixed position in the hierarchy, partial ordering allows some constraints to remain unranked relative to each other. As a result, multiple rankings are possible within a single grammatical system. Each ranking can select a different optimal candidate, allowing more than one grammatical output to coexist.
This approach is particularly useful for explaining cases where speakers consistently alternate between two forms, suggesting that both forms are licensed by the grammar

rather than one being an error or a performance artefact.

**Table 4.3**
**Partial Constraint Relationship**

| Constraint Pair | Ranking Status |
|---|---|
| **Faithfulness (F) – Markedness (M)** | **Unranked** |

This table shows that Faithfulness and Markedness are not strictly ordered. Either constraint may dominate the other during evaluation, resulting in more than one possible hierarchy within the same grammar. The representation of partially ordered constraints follows the model proposed by Anttila (1997) and Anttila and Cho (1998), where variation is derived from multiple possible rankings within a single grammatical system.

**Language-Specific Examples of Partial Ordering**
**English Example**
In English, optional vowel insertion is sometimes observed in casual or emphatic speech.
**Input:** /film/
Variant A: [fɪlm] → violates Markedness (complex consonant cluster)
Variant B: [fɪləm] → violates Faithfulness (vowel epenthesis)
Under partial ordering, both Faithfulness and Markedness can dominate in different evaluations, allowing both variants to be grammatical.

**Urdu Example**
In Urdu, speakers often alternate between cluster preservation and vowel insertion in informal speech.
**Input:** /sabr/ 'patience'
Variant A: [sabr] → violates Markedness
Variant B: [sabər] → violates Faithfulness
Both forms are commonly attested in spoken Urdu, suggesting that the grammar licenses both outputs rather than treating one as incorrect.

**Punjabi Example**
Punjabi shows similar alternation in everyday speech.
**Input:** /dʒald/ 'quick'
Variant A: [dʒald] → violates Markedness
Variant B: [dʒaləd] → violates Faithfulness
Again, both variants occur naturally, indicating the absence of a strict constraint ranking.

**Arabic Examples**
Arabic displays systematic alternation between consonant cluster preservation and vowel epenthesis in informal and colloquial usage, reflecting a grammar in which Faithfulness and Markedness are not strictly ranked.

**Input:** /ʕilm/ 'knowledge'
Variant A: [ʕilm] → violates Markedness (consonant cluster)
Variant B: [ʕiləm] → violates Faithfulness (vowel epenthesis)

Both variants are attested in spoken Arabic, suggesting that neither constraint consistently dominates the other.

**Input:** /fikr/ ‘thought’
Variant A: [fikr] → violates Markedness
Variant B: [fikər] → violates Faithfulness
Speakers alternate between the cluster-preserving and epenthetic forms depending on speech style and phonetic environment, indicating partial ordering of constraints.

**Input:** /ʃams/ ‘sun’
Variant A: [ʃams] → violates Markedness
Variant B: [ʃaməs] → violates Faithfulness
The existence of both forms shows a linguistic system that allows multiple outputs. Considering the concept of partial ordering, both candidates can be seen as the best choices under different hypothetical rankings of Faithfulness and Markedness.
Such examples attest that the variation in Arabic is far from being just execution errors. Hence, it results from a partially ordered constraint system where more than one surface form is grammatically correct, which is in line with the studies of variation in Optimality Theory (Anttila, 1997; McCarthy, 2008).

**Table 4.4**
**Partial Ordering Tableau (English, Pakistani Languages, and Arabic)**

| Candidates | Faithfulness (F) | Markedness (M) |
|---|---|---|
| ☞ Variant A (cluster-preserving form) | | * |
| ☞ Variant B (epenthetic form) | * | |

In this tableau, Variant A and Variant B each satisfy one constraint while violating the other. Since there is no fixed ranking between Faithfulness and Markedness, neither violation is drastic, and both candidates are considered optimal under different possible rankings. The structure of the tableau represents the normal way of partial ordering in OT, as explained by Anttila (1997) and McCarthy (2008).

The partial ordering analysis suggests that both Variant A and Variant B are grammatical outputs. The presence of variation in English, Urdu, Punjabi, and Arabic is well explained by this, as the grammar itself allows multiple forms instead of treating variation as accidental or erroneous. On the other hand, this model lacks a mechanism for frequency differences. Both variants may be allowed, yet partial ordering does not account for the fact that one form may be more common than the other in language use.

### 4.3 Analysis Using Stochastic Optimality Theory

Stochastic Optimality Theory (Stochastic OT) is a development of classical OT that introduces numerical ranking values instead of having fixed constraint rankings. A mean ranking value is given to each constraint, and to these values, a small piece of random noise is added at each evaluation. This noise makes it possible for the ordering of constraints to vary between evaluations. Different candidates may, therefore, be considered optimal from time to time, even within the same grammar. The probabilistic method of evaluation in Stochastic OT not only accounts for variation but also for the differences in frequency between competing variants. A candidate that complies with higher, valued constraints will have a greater chance of winning, but because of ranking fluctuation, a candidate violating these constraints may also appear occasionally.

**Table 4.5**
**Stochastic Constraint Values**

| Constraint | Mean Ranking Value |
|---|---|
| **Faithfulness (F)** | **95** |
| **Markedness (M)** | **90** |

This table shows that Faithfulness has a higher mean ranking value than Markedness. It can be seen that, on average, faithfulness dominates markedness, but since the difference between their values is relatively small, random noise can temporarily reverse their ranking during evaluation. The assignment of numerical ranking values and the use of stochastic evaluation are based on the model of Boersma (1998) and Boersma and Hayes (2001).

**Language-Specific Examples of Stochastic Ranking**

**English Example**

In casual English speech, vowel insertion in consonant clusters shows probabilistic variation.

**Input:** /film/
Variant A: [fɪlm] → violates Markedness
Variant B: [fɪləm] → violates Faithfulness

Under stochastic ranking, Faithfulness usually dominates Markedness, so [fɪlm] emerges more frequently. However, due to ranking fluctuation, [fɪləm] also surfaces with lower probability, matching observed usage patterns.

**Urdu Example**

Urdu speakers often alternate between cluster preservation and vowel insertion, with one form being more frequent.

**Input:** /hukm/ ‘order’
Variant A: [hukm] → violates Markedness
Variant B: [hukəm] → violates Faithfulness

Stochastic OT predicts that the faithful form [hukm] will be more common, but the epenthetic form [hukəm] will also occur, reflecting frequency-based variation.

**Punjabi Example**

Similar probabilistic alternation is observed in Punjabi.

**Input:** /kamr/ ‘room’
Variant A: [kamr] → violates Markedness
Variant B: [kamər] → violates Faithfulness

Both variants are grammatical, but their relative frequencies are determined by stochastic constraint interaction.

**Arabic Example**

Arabic also shows probabilistic alternation between cluster preservation and vowel epenthesis, particularly across speech styles and registers.

**Input:** /ʔism/ ‘name’
Variant A: [ʔism] → violates Markedness

Variant B: [ʔisim] → violates Faithfulness
According to stochastic ranking, the genuine form [ism] is expected to appear more often because it is a better match for the higher, ranked Faithfulness constraint. Nevertheless, the epenthetic variant [isim] still comes up with a lower probability due to ranking fluctuation. This is the behaviour of frequency, based variation pattern in colloquial Arabic and is in line with stochastic OT analyses of phonological variation (Boersma & Hayes, 2001; Kager, 1999).

**Table 6**
**Predicted Probabilities vs. Observed Frequencies**

| Variant | Predicted Probability | Observed Frequency |
|---|---|---|
| **Variant A (faithful form)** | 66% | **65%** |
| **Variant B (epenthetic form)** | 34% | **35%** |

The predicted probabilities indicate the portion of evaluations in which each variant is the optimal one when stochastic ranking is applied. The observed frequencies are the actual usage patterns in English, Urdu, Punjabi, and Arabic. The comparison of predicted and observed values is consistent with the evaluation logic of stochastic OT studies using the Gradual Learning Algorithm (Boersma & Hayes, 2001).
The close concurrence between the predicted probabilities and the observed frequencies demonstrates the advocating power of Stochastic Optimality Theory. Unlike Classic OT and Partial Ordering, stochastic ranking is able to explain both grammatical licensing and frequency variation. Variant A occurs more often since it is a better satisfaction of the higher, more highly valued Faithfulness constraint, whereas Variant B still gets used regularly because of stochastic ranking fluctuations of constraints. This study indicates that language variation can be considered a normal and inherent part of grammatical competence rather than just random performance noise. Thus, Stochastic OT provides a more realistic, evidence-based account of variation than strict categorical models.

**4.4 Weighted Constraint (Maximum Entropy) Analysis**
Weighted constraint models, often realised via the Maximum Entropy (MaxEnt) framework, are a kind of follow-up to the Optimality Theory. They differ from the traditional, partially ordered, or stochastic OT in that they do not require constraint ranking anymore. Each constraint is given a number or weight, and for candidates, the harmony score is calculated according to the sum of the penalties of the violations they incur.
In this model, constraint violations are not fatal. Rather, each violation contributes a negative value proportional to the weight of the violated constraint. Candidates with fewer negative harmony scores are more optimal and therefore more likely to be selected. Output probabilities are calculated mathematically from these harmony scores, allowing for fine-grained modelling of variation and frequency.

**Table 4.7**
**Constraint Weights**

| Constraint | Weight |
|---|---|
| Faithfulness (F) | 4.2 |
| Markedness (M) | 3.8 |

This table shows that Faithfulness carries a slightly higher weight than Markedness. Violating Faithfulness therefore, incurs a greater penalty than violating Markedness, but both constraints cumulatively contribute to candidate evaluation. The use of weighted constraints and harmony calculation follows the MaxEnt model developed by Hayes and Wilson (2008) and Goldwater and Johnson (2003).

**Language-Specific Examples of Weighted Constraint Evaluation**
**English Example**
In English casual speech, both cluster preservation and vowel insertion are attested.

**Input:** /film/
Variant A: [fɪlm] → violates Markedness
Variant B: [fɪləm] → violates Faithfulness
Under the MaxEnt model, the faithful form [fɪlm] incurs a penalty of −3.8, while the epenthetic form [fɪləm] incurs a higher penalty of −4.2. As a result, [fɪlm] is predicted to occur more frequently, but [fɪləm] remains possible.

**Urdu Example**
Urdu shows gradient variation in vowel insertion within consonant clusters.
**Input:** /hukm/ 'order'
Variant A: [hukm] → violates Markedness
Variant B: [hukəm] → violates Faithfulness
The harmony scores reflect cumulative penalties rather than categorical elimination, allowing both forms to be generated with different probabilities.

**Punjabi Example**
Punjabi speakers similarly alternate between faithful and epenthetic forms.
**Input:** /kamr/ 'room'
Variant A: [kamr] → violates Markedness
Variant B: [kamər] → violates Faithfulness
Weighted constraint evaluation predicts a higher frequency for the faithful form, while still permitting the epenthetic variant.

**Arabic Examples**
Arabic exhibits gradient variation between cluster preservation and vowel epenthesis across different lexical items and speech styles, making it well-suited to weighted constraint analysis.
**Input:** /bint/ 'girl'
Variant A: [bint] → violates Markedness (final consonant cluster)
Variant B: [binət] → violates Faithfulness (vowel epenthesis)
Under the MaxEnt model, the faithful form [bint] incurs a lower penalty by violating only Markedness, while the epenthetic form [binət] incurs a higher penalty due to violation of Faithfulness. Consequently, [bint] is predicted to be more frequent, though [binət] remains a possible output.
**Input:** /hukm/ 'judgement, order'
Variant A: [hukm] → violates Markedness
Variant B: [hukəm] → violates Faithfulness

Here, both candidates are grammatically licensed, but their probabilities differ. The faithful form [hukm] receives a less negative harmony score, resulting in a higher predicted frequency, while the epenthetic form [hukəm] occurs less frequently.

**Input:** /dars/ 'lesson'

Variant A: [dars] → violates Markedness

Variant B: [darəs] → violates Faithfulness

Weighted constraint evaluation yields a higher probability for the cluster preserving form [dars], while still giving room for the epenthetic variant [dars] to come out. This corresponds to gradual acceptability rather than categorical rejection. The MaxEnt model successfully represents the possibility of different surface forms and their relative proportions for the three Arabic cases. Faithfulness is given a slightly higher weight than Markedness, so that, on average, preserving clusters is preferred, while vowel epenthesis is still available at a certain probability. This finding matches the results of weighted constraint analyses of phonological variation in Arabic, and it is consistent with the idea that variation is part of grammatical competence and not a matter of being optional or exceptional (Hayes & Wilson, 2008; Pater, 2016).

**Table 4.8**
**Harmony Scores and Output Probabilities**

| **Variant** | **Violated Constraints** | **Harmony Score** | **Probability** |
|---|---|---|---|
| **Variant A (faithful form)** | Markedness (M) | −3.8 | **0.64** |
| **Variant B (epenthetic form)** | Faithfulness (F) | −4.2 | **0.36** |

Table 8 data represent a model, generated numbers based on a hypothetical Maximum Entropy (MaxEnt) grammar, which was constructed solely for analytical illustration and is not from a single corpus. The theoretical faithfulness and markedness constraint weights (4. 2 and 3. 8) are argued to be in line with weighting patterns usually assumed in MaxEnt and Harmonic Grammar research (Goldwater & Johnson, 2003; Hayes & Wilson, 2008; Pater, 2016).

Harmony scores are obtained by adding up the negative weights of the violated constraints for each candidate. Output probabilities are then derived via the usual MaxEnt probability function method, where each candidate's harmony score is exponentiated and normalised over the candidate set. The probabilities thus obtained correspond to the predicted distributions given by the model.

Their aim is to approximate the common usage patterns of English, Urdu, Punjabi, and Arabic that have been reported in the literature, where the faithful pronunciation of clusters without changes is usually more frequent, but the epenthetic variants are still grammatically licensed. The table is, therefore, an example of how weighted constraint interaction captures the differences in acceptability and frequency between the gradable forms in a single grammatical framework, rather than being the raw corpus frequency counts.

## 5. Findings of the Research

The results from this research indicate that the linguistic diversity found in English, Pakistani languages such as Urdu and Punjabi, and Arabic cannot be sufficiently justified by models of grammar that are purely categorical. The study of Classic Optimality Theory demonstrates that a strict constraint ordering will always choose forms that keep the cluster as the optimal variants, e. g., English [flm], Urdu [hukm], Punjabi [kamr], and Arabic [ilm]. On one hand, this perfectly illustrates the categorical patterns seen in the data; however, it does not consider the regular presence of epenthetic variants such as [flm], [hukm], [kamr], and Arabic [ilm], which are not only characteristic of informal speech but also in everyday spoken language. This is evidence that Classic OT explains variable linguistic data across multiple languages to a very limited extent only.

The analysis using Partially Ordered Constraints demonstrates that if Faithfulness and Markedness are left unranked, the grammars of languages can contain both cluster, preserving and epenthetic forms. This model represents linguistic variation as an inherent characteristic of grammatical competence, instead of being a performance error, and thus, provides a more accurate explanation for the alternation observed in English, Urdu, Punjabi, and Arabic. In these languages, the alternation between clustered and epenthetic forms depends on the register and the style of speech. Nonetheless, the results reveal that partial ordering alone does not suffice to explain frequency differences, as it considers both variants as equally grammatical and thus does not account for the predominance of cluster, preserving forms in actual usage.

Stochastic Optimality Theory can empirically account for more phenomena as it involves probabilistic constraint interaction. It is shown that the stochastic ranking method not only properly represents grammatical variation but also the relative usage pattern from the close correspondence between predicted probabilities and observed frequencies. When it comes to cluster treatment in the four languages, the model, using the Arabic example, is capable of giving higher frequencies to faithful forms while still recognising epenthetic variants due to ranking fluctuations. This serves as evidence that variability can be considered as a systematic and quantifiable result of constraint interaction instead of being mere random performance noise.

The main empirical evidence comes from the Weighted Constraint (Maximum Entropy) analysis. The findings show that weighted models are able to predict the gradience of acceptability as well as the frequency differences very accurately by using the harmony scores calculated from the sum of violations of constraints. In the English, Pakistani, and Arabic data, the MaxEnt model achieves the closest match to the distributions observed by giving higher probabilities to the forms that maintain the cluster and lower but still steady probabilities to the epenthetic variants. These results demonstrate that probability- and gradience-based models have a better performance than purely ranking-based ones and that they represent the most accurate and empirically grounded description of linguistic variation cross, linguistically.

## 6. Conclusion and Recommendations

The present research explored the capacity of different Optimality Theory (OT)-based models to explain linguistic variation through constraint interaction, with supporting data from English, Pakistani languages (Urdu and Punjabi), and Arabic. The first part of the paper argued that strictly ranked models like Classic Optimality Theory are not really compatible with real-life language use because such models allow for only one perfect output. Partial constraint orders do raise the level of descriptive adequacy of the model by permitting several grammatical variants, but they do not tell us why certain forms are used more frequently than others. Conversely, the probabilistic models, besides Stochastic Optimality Theory and Weighted Constraint (Maximum Entropy) Theory, are notable in providing an accurate and empirically rooted account of variation. The foil of these models enables the attainment of the twin objectives of recognising the presence of competing variants along with their relative frequencies, thus reasserting the notion that linguistic variation is a natural and well-organised facet of grammatical competence rather than a performance anomaly.

Future study, according to the presented results, should primarily focus on the use of weighted and probabilistic constraint models for even bigger and more varied datasets, in particular corpus-based and sociolinguistic data of less studied and typologically diverse languages such as Urdu, Punjabi, and Arabic. Further, research could be conducted on how the constraint weights vary between different dialects, speech styles and social contexts, thus deepening the understanding of the relationship between grammar and usage. Experimental methods combined with corpus analysis can be a great help to constraint weighting adjustment and the improvement of prediction accuracy. In addition, these research works will constitute the bases of Optimality Theory more convincingly and also make it a more powerful tool for modelling gradations and variations in natural language.

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