Phonological Rule-Learning and Its Implications for a Theory of Vowel Harmony

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1. Introduction

The goal of the current study is to investigate the roles of formal simplicity and phonetic naturalness in the learning of a vowel harmony (VH) pattern. Unlike studies of psychological reality, which examine the competence of native speakers, our learnability study presented new patterns to 'naïve' listeners. We asked our subjects, none of whom had previous exposure to a harmony language, to learn different patterns of non-local vowel interaction by listening to nonce forms in the laboratory. While this experimental procedure does present subjects with a somewhat artificial learning situation, it also buys an important benefit: we can manipulate the form and phonetic naturalness of a pattern, which we cannot do with a pattern that has already been internalized (e.g., palatal and rounding harmony rules for Turkish speakers). We can therefore test hypotheses about formal simplicity and phonetic factors directly.

For formal simplicity, we wanted to determine whether listeners exhibit better learning with phonological patterns that are predictable based on a single feature ("formal simplicity," as schematized in (1)) versus those which are not ("formal complexity," as schematized in (2)).

1. $X_{\alpha} \ldots X \rightarrow X_{\alpha} \ldots X_{\alpha}$
2. $X_{\alpha,\beta} \ldots X \rightarrow X_{\alpha,\beta} \ldots X_{\alpha}$

A *Simplicity Hypothesis,* as we will refer to it, would propose that listeners learn patterns of type (1) more readily than patterns of type (2).

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For phonetic naturalness, we wanted to determine whether listeners exhibit better learning with phonological patterns that are phonetically natural versus those that are phonetically unnatural. By "phonetically natural," we mean a pattern which could conceivably arise from listeners' interpreting the acoustic cues of speech at face value – that is, interpreting them without reference to any grammar. The schema in (3) shows a pattern that could arise if listeners interpret the perseveratory influence of acoustic cues from the first segment as an inherent part of the second segment, while that in (4) shows a pattern which could not arise in such a manner.

3. $X_{\alpha} \ldots X \rightarrow X_{\alpha} \ldots X_{\alpha}$

4. $X_{\alpha} \ldots X \rightarrow X_{\alpha} \ldots X_{-\alpha}$

A *Naturalness Hypothesis* would propose that listeners learn patterns of type (3) more readily than patterns of type (4). This hypothesis is of particular importance because the role of phonetic factors in phonology remains unresolved. Some researchers have advocated theories of phonological competence that directly incorporate phonetic factors such as auditory perception and ease of articulation (e.g., Archangeli & Pulleyblank 1994). But others have rejected such a view, arguing instead that phonetic factors are active only in sound change over time (e.g., Ohala 1974, Hale & Reiss 2000).

Previous experimental research on VH has not directly addressed either the Simplicity or the Naturalness Hypothesis, but has focused instead on the psychological reality of VH for native speakers. Zimmer (1969), for example, showed that Turkish speakers have a strong preference for nonsense roots conforming to VH rules. Yavaş (1980) showed that Turkish speakers apply VH rules to epenthetic vowels in nonsense words and to suffix vowels in foreign words. And Campbell (1986) showed that Finnish speakers apply VH rules to novel inputs in a word game. The ability of native speakers to apply VH productively to novel forms does demonstrate that a rule (rather than, say, memorization) is at work. It does not tell us, however, what form the VH rule actually takes for speakers, or whether formal simplicity and phonetic naturalness influence that form.

Experimental research on non-VH patterns, meanwhile, has provided some support for both the Simplicity and the Naturalness Hypotheses. Schane, Tranel, & Lane (1975) compared the learnability of an attested liaison rule (delete word-final Cs before a following C) with a formally equivalent counterpart (delete word-final Cs before a following V), and found that the liaison rule was learned more quickly and with fewer errors. In a study of local voicing assimilation, Healy & Levitt (1980) found that subjects learned formally simple rules (those which were predictable based on a single feature, [voice]) significantly better than arbitrary rules, but *only* when the rule exhibited assimilation. When the rule did not exhibit assimilation – e.g., when the [voice] feature of a stem-final C conditioned the choice of a suffix V – subjects did not appear to benefit from rule simplicity in their learning. In other words, while subjects learned formally simple rules better than arbitrary rules, their ability to do so seemed to depend upon the content or naturalness of the phonological pattern. The theoretical implication is that phonetic factors may form part of the synchronic phonological grammar.

Although compelling in certain aspects, the results of Healy & Levitt (1980) remain inconclusive. The English-speaking subjects in the study were tested on local voicing assimilation, a pattern to which they had already been exposed in multiple contexts (s/z for plural and possessive, which was used here as a control, but also t/d for past tense). So this phonological pattern was not truly novel, but had been previously learned. Furthermore, from a perceptual point of view, Healy & Levitt (1980) did not really test phonetic naturalness, because subjects were presented with orthographic suffixes, and never actually heard the suffixed forms. We attempted to avoid these problems in our experimental design, by presenting subjects with truly novel patterns delivered in auditory mode from a digitized recording.

2. Experimental design

To investigate the learning of harmony and related rules, we asked our English-speaking subjects to learn patterns of non-local vowel interaction by listening to nonce words. Each word consisted of a CVC stem followed by a VC suffix whose vowel alternated according to the vowel of the stem. Subjects listened to pairs of stem and suffixed forms exhibiting a particular pattern, and were then asked to make judgments about novel pairs of stem and suffixed forms. Correct judgments were taken as an indication of learning. To accomplish the goal of measuring learnability by varying formal simplicity and phonetic naturalness, we devised two different experimental conditions, (5-6) and a control condition, (7).

5. *Palatal Vowel Harmony* (VH): stem and suffix V agree in [back]
After front vowels, front suffix -ɛk: CiC-ɛk, CɪC-ɛk, CæC-ɛk
After back vowels, back suffix -ʌk: CuC-ʌk, CʊC-ʌk, CaC-ʌk

6. *Palatal Vowel Disharmony* (DH): stem and suffix V disagree in [back]
After front vowels, back suffix -ʌk: CiC-ʌk, CɪC-ʌk, CæC-ʌk
After back vowels, front suffix -ɛk: CuC-ɛk, CʊC-ɛk, CaC-ɛk

7. *Palatal Arbitrary* (ARB): stem and suffix V may agree or disagree in [back], depending upon what the stem V is.

After [i, æ, ʊ], front suffix -ɛk:	CiC-ɛk, CæC-ɛk, CʊC-ɛk
After [ɪ, u, a], back suffix -ʌk:	CɪC-ʌk, CuC-ʌk, CaC-ʌk

The Harmony and Disharmony conditions present patterns of equal formal simplicity. The value of the feature [back] in the stem vowel predicts the value of that same feature in the suffix vowel. No further information is needed. Schematically, if α is the value of [back], then in VH, $X_{\alpha}\ldots X \rightarrow X_{\alpha}\ldots X_{\alpha}$. In DH, the predictive power of [back] is equivalent: $X_{\alpha}\ldots X \rightarrow X_{\alpha}\ldots X_{-\alpha}$.

The Arbitrary condition, on the other hand, presents a pattern of greater formal complexity than either VH or DH. One possible rule formulation for the Arbitrary Condition involves table look-up, as in (8a). Other rule formulations could map stem vowels onto suffix vowels according to height and backness, as in (8b) where the 'mid' vowels are [ɪ, ʊ], or feed strings into a harmony or disharmony process according to height, as in (8c). The point, of course, is that regardless of how we state the Arbitrary rule, its formulation remains more complex than that of the Harmony or Disharmony rules.

8a. i…X → i…ɛ
ɪ…X → ɪ...ʌ
etc.

8b. [-back, -mid]…X → [-back, -mid]…ɛ
[+back, +mid]…X → [+back, +mid]…ɛ
[-back, +mid]…X → [-back, +mid]…ʌ
[+back, -mid]…X → [+back, -mid]…ʌ

8c. [+ mid]…X → *Disharmonize*
Else → *Harmonize*

Although the Harmony and Disharmony conditions are similar in terms of simplicity, they differ from one another – and from the Arbitrary condition – in terms of phonetic naturalness. Words in the VH condition exhibit feature agreement between subsequent vowels; such agreement could conceivably reflect the tendency of acoustic cues to spread across VCV sequences during coarticulation. We therefore refer to the VH condition as phonetically natural. Words in the DH condition, on the other hand, exhibit feature disagreement. No strictly phonetic tendency, on its own, could account for such disagreement, so we refer to the DH condition as phonetically unnatural. An interesting characteristic of the Arbitrary condition is that *some* of the words in it can be considered phonetically natural (CiC-ɛk, CæC-ɛk, CuC-ʌk, CaC-ʌk) while others cannot (CʊC-ɛk, CɪC-ʌk).

Finally, none of the patterns in (5-7) has a productive counterpart in English, an important requirement in a learnability study with English-speaking subjects. The experimental conditions are summarized in (9).

9. Characteristics of experimental conditions

	Harmony	**Disharmony**	**Arbitrary**
Predictable based on a *single* feature?	✓	✓	×
Phonetically natural?	✓	×	✓ for some forms × for other forms
Direct counterpart in English?	×	×	×

Stimuli

The stem Vs included front [i, ɪ, æ] and back [u, ʊ, a]. The suffix Vs alternated between [ɛ] and [ʌ]. To control for coarticulatory effect of consonants Cs on Vs, consonants included a representative selection from English. The following pairs were used: [b_g, c_b, g_p, m_t, s_n, t_k, f_n, n_c]. Stimuli were recorded by phonetically-trained native speaker of American English using normal prosody, and digitized at 44,100 kHz.

Each token consisted of one stem, followed by 0.3 seconds of silence, followed by the corresponding suffixed form. Splicing to create tokens was performed in Praat. Sample tokens are in (10-12).

10. Sample correct tokens for Harmony condition (= incorrect tokens for Disharmony condition)

[gip…gip-ɛk]	[sun…sun-ʌk]
[mɪt… mɪt-ɛk]	[tʊk…tʊk-ʌk]
[bæg…bæg-ɛk]	[fan…fan-ʌk]

11. Sample correct tokens for Disharmony condition (= incorrect forms for Harmony condition)

[gip…gip-ʌk]	[sun…sun-ɛk]
[mɪt… mɪt-ʌk]	[tʊk…tʊk-ɛk]
[bæg…bæg-ʌk]	[fan…fan-ɛk]

12. Sample correct tokens for Arbitrary condition

[gip…gip-ɛk]	[sun…sun-ʌk]
[mɪt… mɪt-ʌk]	[tʊk…tʊk-ɛk]
[bæg…bæg-ɛk]	[fan…fan-ʌk]

Subjects

Subjects were native speakers of American English with no background in linguistics (n=30), who were paid for their participation. Some had experience with a second language, but none possessed any previous knowledge of a harmony language. To minimize the effect of individual differences in cross-linguistic learning (cf. Beddor & Gottfried 1995), subject groups in each condition (n=10) were balanced according to performance on an unrelated phonological learning task, administered as a pre-test.

Procedure

Subjects were told that they were listening to singular-plural pairs in a new language, and that their task was to learn how to make plurals in this language. The procedure was presented by E-Prime software, to subjects who were seated in front of a computer monitor wearing headphones. The procedure consisted of three parts: a listening session, a learning session with feedback, and a testing session with no feedback.

The goal of the listening session was simply to expose subjects to correct singular-plural pairs. They listened to 18 tokens, each repeated twice (18 x 2 = 36). Only grammatically correct forms were presented. After each token, subjects pressed a button to indicate readiness to continue. Next, the goal of the learning session was to train subjects interactively, by asking them to make word-formation judgments and providing them with feedback. Subjects listened to 36 tokens, some novel and some 'old' (i.e., presented during the previous listening session), each repeated twice (36 x 2 = 72). Half of the tokens were grammatically correct, half were incorrect. After each token, subjects pressed one button if the singular-plural pair was correct or another button if it was incorrect. Automated feedback informed subjects if their response was right or wrong. Finally, the goal of the testing session was to measure each subject's ability to generalize the pattern they had heard, with no further training or feedback. The task was identical to that of the learning session, but with 36 completely novel tokens, each repeated twice (36 x 2 = 72). Again, after each token, subjects pressed one button if the singular-plural pair was correct or another button if it was incorrect. No feedback was presented during this final session.

Subjects spent about 15-20 minutes total on this procedure. Afterwards, we conducted post-test debriefing sessions with each subject.

Note that the procedure used here introduces a set of data, or a 'puzzle', which subjects are asked to solve. Further work would be required to demonstrate that the learning strategies which subjects used in this procedure are, in fact, the same strategies that speakers use when learning natural language. See Wilson (this volume) for an alternative procedure to test the learnability of phonological patterns.

Hypotheses

The three experimental conditions allow us to test the hypotheses introduced earlier:

A. **Simplicity Hypothesis:** Predictability based on a single feature affects learning. Therefore, we expect better learning rates in both the Harmony and Disharmony conditions than in the Arbitrary condition.

B. **Naturalness Hypothesis:** Phonetic naturalness affects learning. Therefore, we expect better learning rates in the Harmony condition than in the Disharmony and Arbitrary conditions.
Corollary: We might also expect that just those vowel-to-vowel correspondences in the Arbitrary condition which exhibit harmony are more easily learned than those which do not.

C. **Null Hypothesis:** Neither of these factors affects learning. Therefore, we expect comparable learning rates in all three conditions.

Note one caveat to these predictions. Formal simplicity and phonetic naturalness are often conflated. In order to completely disentangle these two factors from one another, we would need an additional experimental condition that exhibited formal simplicity alongside another characteristic, such as a long-distance dependency, which created a phonetically unnatural situation: e.g., a suffix that alternates based on a feature value in the *initial* segment of a word. We hope to test this condition in future work.

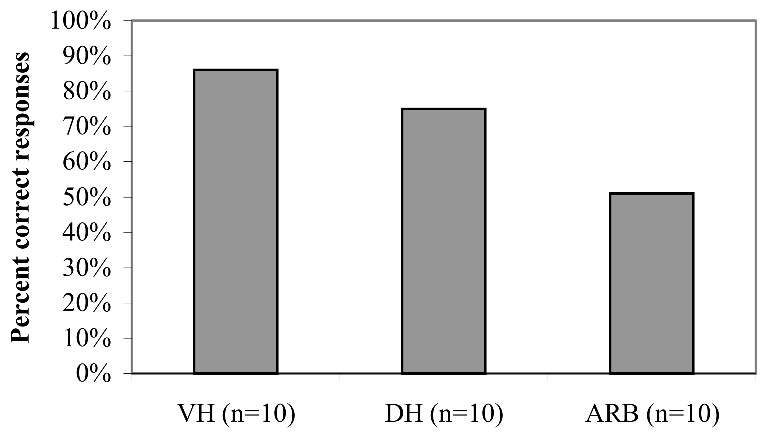
3. Results

Overall, results provide support for the Simplicity Hypothesis, but do not provide support for the Naturalness Hypothesis. Subjects demonstrated significantly better learning in the Harmony and Disharmony conditions when compared with subjects in the Arbitrary condition. No other differences were significant. The data in (13) shows the mean raw scores and percent correct for subjects in each of the three conditions. The graph in (14) displays the same percent correct figures.

13.

	Harmony	**Disharmony**	**Arbitrary**
Mean number of correct responses (out of 72 total responses)	62	54.1	36.5
Mean % correct	86%	75%	51%
Standard deviation	11.18	14.12	14.01

14.

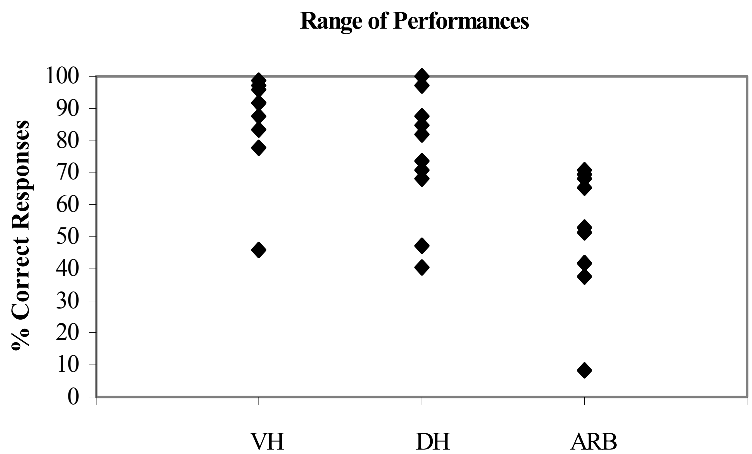


The results were first analyzed using a one-way analysis of variance. It revealed a significant difference, $F(2, 27) = 9.820$, $p = .001$. Post-hoc test (Tukey's HSD and Scheffe) both revealed significant differences between the Harmony condition and the Arbitrary condition ($p = .001$) and between the Disharmony condition and the Arbitrary condition ($p = .016$). The difference between the Harmony condition and the Disharmony condition was not significant ($p = .385$).

Since the distribution of scores appeared to differ from normal distribution, the scores were rank-ordered and subjected to non-parametric tests, which yielded the same result as the ANOVA. A Kruskall-Wallis test revealed a statistically significant difference between the three conditions ($\chi^2 = 13.051$ (2, N = 30), $p = .001$). In order to discover which conditions were significantly different from one another, pairwise comparisons were also made using the Mann-Whitney U test. They revealed significant differences between the Harmony condition and the Arbitrary condition ($U=6$, $p=.001$) and between the Disharmony condition and the Arbitrary condition (U=17, p=.013), but not between the Harmony condition and the Disharmony condition (U=31, p=.15).

The performance of all thirty subjects is shown in (15). Note that one subject in the Arbitrary condition performed at about 10% correct, a result of her failure to respond to many stimulus items during the testing session.

15.



Conclusions from overall results

The presence of feature predictability did play a role in learning. Subjects in the Harmony condition exhibited significantly better learning than those in the Arbitrary condition. Likewise, subjects in the Disharmony condition exhibited significantly better learning than those in the Arbitrary condition. On the other hand, phonetic naturalness did not appear to play a role in learning. Subjects in the Harmony and Disharmony conditions did not produce significantly different results from one another. The lack of a statistically significant difference between these groups should be interpreted with caution, however. It is possible that a larger subject pool could reveal differences.

It is also possible that, given longer exposure to the stimuli, subjects in the Arbitrary condition would eventually demonstrate the ability to apply the Arbitrary pattern to novel forms, with a correctness rate comparable to subjects in the other conditions. We would in fact expect such a result, since we know that speakers can and do learn such arbitrary patterns in their native language. The point of investigating subjects in a laboratory setting, however, was to uncover those learning biases which manifest themselves right away – here, within 15-20 minutes of exposure to novel forms. Within this timeframe, subjects in the Arbitrary condition demonstrated significantly poorer learning than subjects in the other two conditions, and results confirmed the Simplicity Hypothesis.

Analysis of errors

The total number of errors made in each condition, for each stimulus type, is shown in (16-18).

16. Harmony: Distribution of errors

CiC-ɛk	**CɪC-ɛk**	**CæC-ɛk**	**CuC-ʌk**	**CʊC-ʌk**	**CaC-ʌk**
12	16	12	12	8	38

17. Disharmony: Distribution of errors

CiC-ʌk	**CɪC-ʌk**	**CæC-ʌk**	**CuC-ɛk**	**CʊC-ɛk**	**CaC-ɛk**
28	23	36	20	28	44

18. Arbitrary: Distribution of errors

CiC-ɛk	**CɪC-ʌk**	**CæC-ɛk**	**CuC-ʌk**	**CʊC-ɛk**	**CaC-ʌk**
46	57	35	57	92	78

In each case, a χ^2 test was performed to determine whether there are statistically significant differences in the distribution of errors between the six root vowels. The results were significant in all cases. In the Harmony condition χ^2 (5) = 36.44, p<.001. In the Disharmony condition χ^2 (5) = 13.02, p<.025. In the Arbitrary condition χ^2 (5) = 35.87, p<.001.

In Section 2, we proposed a corollary to the Naturalness Hypothesis. That is, if phonetic naturalness affects learning, we might also expect that just those vowel-to-vowel correspondences in the Arbitrary condition which exhibit harmony (naturalness) are more easily learned than those which do not. Table (18) shows that this prediction is not confirmed. Examination of the two disharmonic forms, [CɪC-ʌk] and [CʊC-ɛk], shows that subjects did make the greatest number of errors (=92) in [CʊC-ɛk] forms, which are disharmonic. But they made a relatively smaller number of errors (= 57) in [CɪC-ʌk] forms, which are also disharmonic, and this number is less than or equal to errors made in the harmonic forms [CaC-ʌk] and [CuC-ʌk]. Thus these error patterns are consistent with the overall learning patterns; that is, phonetic naturalness does not appear to play a role.

One peculiarity of the error distribution is worth mentioning. In the Harmony condition, subjects made a disproportionate number of errors (=38) with words of the form [CaC-ʌk], suggesting that they may have experienced difficulty grouping [a] with the other back vowels [u] and [ʊ]. It seems unlikely that this difficulty was due to height differences alone, because we do not see a similar pattern when we compare the errors made with [æ] to errors with the other front vowels [i] and [ɪ]. It is perhaps more likely that the difficulty arose because of the rounding differences found in the back group ([u] and [ʊ] are round whereas [a] is not) [1]. Such differences are not found in the front group, where all vowels are unrounded. This scenario could also explain the disproportionately high number of errors made with the [CʊC-ɛk] forms in the Arbitrary condition (= 92). If subjects had a tendency to place [u] and [ʊ] together in the same group, they might, as a consequence, have a tendency to make errors in a novel language which requires them to be treated separately, as the Arbitrary condition did.

4. Discussion and theoretical implications

Our experiment confirmed the Simplicity Hypothesis by showing that naïve listeners learned phonological processes that exhibited single-feature predictability significantly better than those processes that did not. Our experiment did not, however, confirm the Naturalness Hypothesis: subjects did not learn a phonetically natural process significantly better than a phonetically unnatural one. As mentioned above, we must interpret this null result with caution; further work with a larger number of subjects will be needed.

Keeping this cautionary note in mind, we can tentatively state that, given brief exposure to nonce forms in laboratory conditions, harmony and disharmony appear to be equivalently learnable patterns. This finding suggests that phonetically natural processes are *not* more 'cognitively accessible' to listeners than unnatural ones. It further suggests that phonetic factors may not have a privileged role to play in a synchronic grammar.

This brings us to the question of why harmony patterns are more widely attested than disharmony patterns cross-linguistically. The answer, according to the findings of the present study, would not appear to lie in phonetic naturalness, or in synchronic factors at all. The explanation may instead be a diachronic one: assimilatory patterns arise when listeners hypo-correct the speech signal for the effects of coarticulation, while dissimilatory patterns arise when listeners hyper-correct the signal unnecessarily (Ohala 1993). According to such an account, hyper-correction only (or usually) involves features which extend over a relatively

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[1] Alternatively, the difficulty may stem from orthographic bias. The stem vowels [u] and [ʊ] can both be represented as orthographic "u" (*rude, pudding*), but [a] obviously cannot. We did not present orthographic stimuli in this experiment, nor did we give any instructions to visualize stimuli orthographically, although some subjects indicated during the debriefing sessions that they had done so anyway.

long time window, such as secondary articulations; dissimilation thus arises relatively infrequently. Assimilation, however, is not subject to such restrictions and arises relatively frequently.

The results of this experiment do have synchronic implications, however. Our study suggests that predictable processes (that is, predictable based on a single feature) *are* more cognitively accessible than non-predictable ones. This idea has been expressed, implicitly at least, in previous work on harmony. Suomi (1983), for example, argued that VH in Finnish arose to provide better perceptibility conditions for front vowels in non-initial positions. Because the initial vowel of a Finnish word helps listeners *predict* the [back] feature of subsequent vowels, he claimed, listeners achieve enhanced perception of these vowels. Although Suomi himself does not discuss disharmony, his predictability argument could and should apply equally well to a disharmonic system (although the difference between root-internal constraints and productive affixing processes would need to be investigated further).

The notion that harmony and disharmony are somehow equivalent processes has found more explicit expression in Pulleyblank's (2002) recent proposal to unify harmony and the Obligatory Contour Principle (OCP) using a single set of 'Don't Disagree' constraints. Pulleyblank suggests that articulatory constraints provide the functional motivation for this unification, but it seems unlikely that such constraints could underlie *both* harmony and disharmony at the same time. Our work points toward a different motivation for such a theoretical proposal: a 'natural class' of rule types. Harmony and Disharmony form a natural class by virtue of the fact that they are equivalent in terms of formal simplicity, a trait which demonstrably affects learning.

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