Analogical effects in regular past-tense production in Dutch

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Abstract

This study addresses the question to what extent the production of regular past-tense forms in Dutch is affected by analogical processes. We report an experiment in which native speakers of Dutch listened to existing regular verbs over head-phones, and had to indicate which of the past-tense allomorphs, te or de, was appropriate for these verbs. According to generative analyses, the choice between the two suffixes is completely regular, and governed by the underlying [voice]-specification of the stem-final segment. In this approach, no analogical effects are expected. In connectionist and analogical approaches, by contrast, the phonological similarity structure in the lexicon is expected to affect lexical processing. Our experimental results support the latter approach: All participants created more non-standard past-tense forms, produced more inconsistency errors, and responded more slowly for verbs with stronger analogical support for the non-standard form [1].

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1. Introduction

A great many studies have addressed the question how to account for regular and irregular word formation. In the traditional view (e.g., Halle 1973; Aronoff 1976; Pinker & Prince 1988; Marcus, Brinkman, Clahsen, Wiese & Pinker 1995; Pinker 1999; Marcus 2001), regular complex forms are the result of productive morphological rules. Irregular complex forms fundamentally differ from the regular forms in that they must be stored in the speakers' mental lexicons, and cannot be created by means of rules.

In contrast to this traditional view of the division of labor between rule and rote, many researchers (e.g., Bybee 1985; 2001, Skousen 1989, 1993; MacWhinney & Leinbach 1991; Daelemans, Gilles & Durieux 1994; Seidenberg & Hoeffner 1998; Plunket & Juola 1999; Plaut & Gonnerman 2000; Seidenberg & Gonnerman 2000; Ramscar 2002) argue that both irregular and regular complex forms are available in the speakers' lexicons, and that no lexicon-independent rules are required. In these approaches, new forms are extrapolated from the lexicon either by similarity-based general analogical processes (Skousen's AML, Daelemans' TiMBL) or by artificial neural networks in which rules and representations are merged. In what follows, we will refer to these schools as analogical accounts, since they assume that the similarity structure in the data is of crucial importance.

The production of the past-tense in English has figured as a testing ground for ascertaining the merits of the rule-based and analogy-based accounts (e.g., Marcus et al. 1995; Pinker & Prince 1991; Pinker 1991, 1997, 1999; Jaeger, Lockwood, Kemmerrer, Van Valin & Murphy 1996; Rumelhart & McClelland 1986; Albright & Hayes 2001). The aim of the present paper is to contribute to the debate on the role of analogy in word formation. We

also call attention to the production of past tense forms, but, unlike abovementioned studies, we do not concentrate on the differences or similarities between regular and irregular past-tense forms, but on the possibility that analogical processes pervade even completely regular past-tense production, irrespective of irregular past-tense formation.

The allomorphy of the Dutch past-tense suffix constitutes a classical example of a completely regular simple morphological rule in Dutch morphology. Past-tense forms are created by suffixing the allomorphs /tə/ te or /də/ de to the verb stem. The allomorph /tə/ is added when the stem ends in an underlyingly voiceless obstruent, or in other words, when the stem ends in a voiceless obstruent before the infinitive suffix /ən/ en. The suffix /də/ is suffixed elsewhere (e.g., Trommelen & Zonneveld 1979: 119; Wetzels 1982: 125; Booij 1995: 61). This is illustrated in (1). We refer to the past-tense forms that obey this simple rule as the standard forms, since these forms are correct according to the Dutch spelling conventions. They contain the standard, conventionalized suffix. Note that this terminology implies that the term standard suffix sometimes refers to [tə] and sometimes to [də], depending on the verb stem. The standard forms are stored in the speakers' lexicon, as appears from Baayen, Schreuder, De Jong and Krott (2002), and Baayen, McQueen and Schreuder (2003).

(1) Verb stem   Singular past-tense form

    rook   /rok/   'smoke'   rookte   /roktə/   'smoked'

    stop   /stɔp/   'stop'   stopte   /stɔptə/   'stopped'

    klaag   /klaɣ/   'complain'   klaagde   /klaɣdə/   'complained'

    roof   /rov/   'steal'   roofde   /rovdə/   'stole'

    kam   /kɑm/   'comb'   kamde   /kɑmdə/   'combed'

The experiment presented in this paper is a follow up of two previous experiments on regular past-tense production in Dutch. The first experiment (Ernestus & Baayen 2003) is similar to Berko's (1958) wug -wugs experiments. Berko presented pseudo-words to English speaking children, such as wug, asking them to create the plural forms of these words (wugs). The children consistently added the appropriate suffixes to the new words. This result is generally interpreted as supporting the view that children have morphological rules at their disposal. In this first experiment on past-tense production in Dutch, we presented native speakers of Dutch with the stems of pseudo-words, e.g., [dɑup], [dɔrx], and [dɪnt], asking them to create the past-tense forms of these pseudo-verbs. Like the children in Berko's experiment, our participants were able to perform this task: They were able to create past-tense forms. At first sight, these results constitute just another piece of evidence for the existence of morphological rules. However, the facts are not that simple.

From a rule-based perspective, it is in fact surprising that the participants were able to perform this task at all. Their task was far more complicated than the task that the children had to perform in Berko's experiment. Like the children in Berko's experiment, our participants had to choose between affixes, but unlike the children, they did not have enough information at their disposal to simply apply the morphological rule. Application of the rule depends on the availability of the underlying [voice]-specification of the stem-final obstruent. This information was not available to our participants. They heard the first person singular present-tense forms of the pseudo-verbs, which do not allow participants deduction of the underlying [voice]-specification of the stem-final obstruents: The stem-final obstruents were

word-final in these forms, and all word-final obstruents in Dutch are realized as voiceless (a phenomenon often referred to as Final Devoicing). Since pseudo-verbs do not have lexical representations, the participants could also not retrieve the underlying [voice]-specifications from their mental lexicon.

Inspection of the created past-tense forms showed that the participants based their choice between te and de on the phonological neighborhoods for the presented pseudo-verbs. They tended to choose te for a given pseudo-verb if the majority of phonological neighbors underlyingly end in voiceless obstruents, and they tended to choose de if the majority of neighbors underlyingly end in voiced obstruents. The relevant phonological neighbors end in an obstruent of the same manner and place of articulation as the experimental verb, and their final obstruent is preceded by consonants of the same sonority, and vowels of the same phonological length as in the experimental verb. We will refer to these phonological neighbors that affect processing as the analogical, phonological gang. In conclusion, the participants based their choice between the two past-tense allomorphs on analogy. In Ernestus & Baayen (2002), we show that participants are also influenced by the analogical gangs when final obstruents in the experiment have some acoustic characteristics of voiced obstruents, i.e., when the signal provides information of the underlying [voice]-specifications of the final obstruents.

Rule-based theories might offer the following explanation for the data from this experiment with pseudo-verbs. The participants may first have determined the underlying [voice]-specifications of the pseudo-verbs by means of analogy. Once analogical processes have delivered an underlying [voice]-specification, this specification completes the input for the symbolic rule, which can now attach [tə] after underlyingly voiceless obstruents and [də] after

underlyingly voiced obstruents.

Rule-based accounts predict that when speakers do have access to the underlying [voice]-specification of the stem-final obstruent, they should not rely on analogy. In other words, analogical effects should not be observed for existing words. When speakers have to create the past-tense forms of existing words, they do know the underlying [voice]-specifications of the stem-final obstruent, since these specifications are stored in their mental lexicons. Having retrieved the stem from memory, they can simply apply the rule, without analogy coming into play.

Ernestus & Baayen (2001) is a first, off-line study investigating whether speakers indeed do not show analogical effects when they create the past-tense forms of existing verbs. The participants in that experiment heard the first person singular present-tense forms of existing verbs, instead of pseudo-verbs, and they were again asked to create the past tense forms. Contrary to the prediction of the rule-based account, this experiment again revealed analogical effects. The participants did not always use the past-tense allomorph that one would expect given the underlying [voice]-specification of the final obstruent in standard Dutch. They tended to produce an unexpected past-tense form when a verb underlyingly ends in a voiced obstruent while most words in the analogical gang of phonologically similar words underlyingly end in voiceless obstruents. In this case, participants tend to attach [tə] instead of the expected [də]. Similarly, participants tend to attach [də] instead of the expected [tə] to a verb with an underlyingly voiceless final obstruent for which the phonological gang favors [də]. For instance, several participants reported <u>dubte</u> as the past-tense form for /dʏb/ <u>dub</u> 'waver', and <u>bliefte</u> as the past-tense form for /bliv/ <u>blief</u> 'like'. Conversely, they created

juichde as the past-tense form for /jœyx/ juich 'cheer'.

Proponents of rule-based accounts might argue that these results only hint at the extension of analogical effects to existing words. Analogical effects might have emerged only because some participants did not know the underlying [voice]-specifications for all stem-final obstruents. Several participants were speakers of varieties of Standard Dutch in which all fricatives tend to be realized as voiceless. Such speakers might only distinguish between stems underlyingly ending in voiced and voiceless fricatives on the basis of the spellings of these stems. If these spellings are not firmly stored in their mental lexicons, these speakers might be uncertain about the underlying [voice]-specification of the stem-final obstruent. If so, they would be forced to fall back on analogy. Moreover, some of the words presented in the experiment are fairly low-frequency verbs. For at least some participants, these words might effectively have been pseudo-verbs, for which they consequently had to fall back on analogy in order to determine the most likely underlying [voice]-specification for the stem-final obstruent.

The experiment that we report in the present paper is a direct follow-up of this experiment. It differs in three respects. First, we presented plural present-tense forms to our participants, instead of singular present-tense forms. Plural present-tense forms in Dutch consist of the verb stem plus the suffix /ən/ en. In these forms, the stem-final obstruent is realized in accordance with its underlying [voice]-specification. The participants, therefore, could determine the underlying [voice]-specification of the stem-final obstruents simply on the basis of the acoustic signal. They are literally told over the headphones what the underlying [voice]-specification is.

Second, we distinguish three groups of participants. The first group of participants make a fairly systematic distinction between underlyingly voiced and voiceless fricatives. We refer to these participants as the [+F] group. They should be able to easily perceive the difference between the voiced and voiceless variants of all types of obstruents, and consequently they should be able to apply the rule in all cases. It is for these participants that the rule-based account predicts no effect of analogy. The second group of participants consists of speakers who do not make any distinction between voiced and voiceless fricatives. This group will be referred to as the [-F] group. The speakers of this group may have problems determining the standard past-tense suffix for stems with final fricatives, since they may be uncertain about the underlying [voice]-specifications of these final obstruents. Under the rule-based account, these are the participants for which analogical effects might be observed for fricative-final stems. The third group of participants ([± F]) realizes the distinction, but does not do so systematically.

Third, we asked our participants to perform two tasks. They first had to make their choice between [də] and [tə] known by pressing a te button or a de button. Following their button-press, they had to write down the past-tense form. In this way, we obtained four dependent variables for every verb: the participants' choices as reflected by the written forms, the differences between the choices reflected by the written forms and by the button presses, the time the participants needed to press a button, and the proportion of trials for which the participants produced time-out errors.

This experiment allows us to investigate whether participants still show analogical effects, that is, effects of gangs of phonologically similar words, under these new experimental con-

ditions, which is not expected under a rule-based account. That is, the experiment allows us to investigate whether the rule-based account is correct in that speakers might reveal effects of analogy only when, for whatever reasons unrelated to analogy, they do not have access to the underlying [voice]-specification of the stem-final obstruent. To falsify this rule-based account, we have to show that the phonological gangs correctly predict for which words participants produce non-standard past-tense forms. Similarly, analogical gangs affecting the reaction times across the board, even for standard past-tense forms, would count against the rule-based approach.

This new experiment will also allow us to investigate the appropriateness of analogical models, theories that assign a key role to the analogical similarity structure of the lexicon, and that do not posit separate morphological rules. Broadly speaking, we can distinguish two classes of analogical approaches, symbolic classifiers and subsymbolic classifiers. The first class comprises instance-based models, of which Daeleman's TiMBLE (1994, 2002) and Skousen's AML (1989, 1993) have proved to be especially useful for the analysis of linguistic data. These two symbolic models make use of an instance base of stored representations. For our data, this instance base can be conceived of as a lexicon of verbs, which for each verb specifies the phonological properties of the stem and the past-tense allomorph required by this verb. In addition to such an instance base, AML and TiMBL supply a classification algorithm. This classification algorithm determines, for a given verb (existing or non-existing), which verbs in the lexicon are most similar, and may form an analogical gang. The classification algorithm assigns a probability to each of the two allomorphs equal to the proportion of verbs in such an analogical gang in which they are realized. The algorithm selects the

allomorph with the highest probability as the most likely choice.

In standard applications of these models, the analogical classification algorithm is called upon only when the required past-tense form is not available in the lexicon. In other words, from a psycholinguistic perspective, we are dealing with a cascaded model in which analogy applies only when retrieval from memory fails. Baayen, Burani & Schreuder (1997), and Baayen, Dijkstra & Schreuder (1997), however, argue that it is unfruitful to stagger memory retrieval and computation. They present evidence that there is far more synergy between the computational route and the memory route in lexical processing than cascaded dual route models would suggest.

We therefore consider a slight modification of these symbolic classification models. We consider a model in which two sources of information are used in parallel: the information provided by the form stored in memory (the standard form), and the information provided by analogical gangs. We allow these two sources to be weighted differently. The standard form is the form taught at school and enforced by the orthographic conventions of Dutch. So, we expect that this source of information may have considerably more weight. Hence, our non-cascaded model predicts that analogy should favor a non-standard form with considerable strength before it can actually be selected. Moreover, it predicts that the choice for a non-standard form should also require more time than a choice that follows the standard. Finally, our model, which takes both the stored forms and the analogical forms into account, predicts that a stronger analogical support for the selected allomorph should result in shorter response latencies. Note that this implies the strong claim that analogical effects should be demonstrable in the response latencies of our experiment even when the participants select

the standard allomorph, i.e., even when their choice by itself suggests that they have simply retrieved the standard form from memory.

Similar predictions follow from sub-symbolic classifiers. When an artifical neural network is trained to map past-tense forms onto present-tense forms, the weights in the network will assume values that support the standard forms. Gang effects due to patterns of similarities shared by the input and output vectors may arise, but with appropriate parameter settings these gangs can be made to have a relatively weak effect. Consequently, there may be competition between the standard and the non-standard form, but non-standard forms will be exceptional. The network will require more cycles to reach a stable state for a non-standard form, and the stronger the gang's favor for the non-standard, the more likely a stable state will be reached for the non-standard form. In addition, the network will also require more cycles to reach a stable state for the standard form if the analogical gang favors the non-standard.

Since symbolic and sub-symbolic classifiers offer similar predictions, we will remain agnostic as to which approach might be preferable. We have opted for using a theory-independent non-parametric classifier to operationalize the notion of analogy. We determined the phonological gangs by means of a Classification Tree (CART: Breiman, Friedman, Olshen & Stone 1984; see also Clark & Pregibon 1992). The input for the CART analysis was a set of some 1700 monomorphemic stems extracted from the CELEX lexical data base (Baayen, Piepenbrock & Gulikers 1995). For each stem, the CART tree had to predict the [voice] specification of the final obstruent on the basis of the segments in the final rhyme: the vowel, the pre-final consonant, if present, and the final obstruent. The CART analysis re-

sulted in a cross-validated classification tree that grouped the 1700 stems into 11 sets of words that share similar rhymes and that have a similar preference for a voiced final obstruent. In what follows, we take these sets to be a first approximation of the phonological gangs. The proportion of stems in a gang with final voiced obstruents represents the analogical support (probability) for a final obstruent to be voiced. The gangs are defined in such a way that they not only embrace all existing words, but also non-existing, and even phonotactically impossible words. They consequently make predictions for existing as well as non-existing words. In the study of Ernestus & Baayen (2003), the probabilities correlated well with the proportion of participants interpreting the final obstruents of 192 pseudo-words as voiced ($r_s = 0.50, p < 0.001$). (This study also discusses more sophisticated theory-dependent formalizations of analogy.)

Table 1 summarizes the analogical gangs of phonologically similar words in terms of the segments of the final rhyme. The segments enclosed by the first pair of brackets represent the vowel, and the segments enclosed by the second pair of brackets the prefinal consonant, with a hyphen indicating the absence of a pre-final consonant. The final pair of brackets encloses the final obstruent. The P represents bilabial plosives, the T alveolar plosives, the S alveolar fricatives, the F labiodental fricatives, and X velar fricatives.

<div style="text-align:center">INSERT TABLE 1 ABOUT HERE</div>

We now turn to our experiment, pitting the predictions of the rule-based account against those of the analogy-based accounts.

2. Introduction

Participants. Forty participants, mostly undergraduates at Nijmegen University, were paid to take part in the experiment. All were native speakers of Dutch. At the end of the experiment, they were asked to read aloud the following list of words: lachen /lɑxən/ 'to laugh', leger /leɣər/ 'army', richel /rɪxəl/ 'ledge', bogen /boɣən/ 'bows', Pasen /pazən/ 'Easter', wazig /ʋazɪx/ 'hazy', racen /resən/ 'to race', vezel /vezəl/ 'fibre', boffen /bɔfən/ 'to be lucky', leven /levən/ 'to live', puffen /pʏfən/ 'to pant', rover /roʋər/ 'robber'. The participants' realizations were taped, and the intervocalic fricatives were transcribed by two native speakers of Dutch as voiced or voiceless. Twenty-four participants realized, according to both transcribers, at least two underlyingly voiced fricatives of different places of articulation as voiced, while realizing all underlyingly voiceless fricatives as voiceless. These participants can probably systematically distinguish between underlyingly voiced and voiceless fricatives. We will refer to these participants as the [+F] participants. Eleven participants invariably realized all fricatives as voiceless. They appear not to distinguish between underlyingly voiced and voiceless fricatives. These participants are referred to as the [-F] group. The remaining five participants form an intermediate group ([± F]): They do not distinguish systematically between underlyingly voiced and voiceless fricatives. We excluded participants from Limburg from our experiment, since in several varieties of Dutch spoken in this part of the Netherlands, the past-tense forms of all verbs are created with the suffix de.

Materials. We selected all monosyllabic verbs from the CELEX lexical data base (Baayen et al. 1995) that end in an obstruent, have regular past-tense forms, and can be combined with the subject pronoun wij 'we'. We discarded the verbs ending in /k/, since these verbs cannot

show analogical effects. The obstruent /k/ has no voiced counterpart, and verbs ending in /k/ are consequently always followed by te. We also discarded low register, informal, words.

The 176 selected verbs, 96 of which have te, and 80 of which have -de as their standard past-tense suffix, are listed in the Appendix. In this Appendix, we also listed the frequency of the past-tense form of each verb, which we define here as the number of occurrences of the verb stem followed by a past-tense suffix in the Dutch part of the CELEX lexical data base. We conflated the frequencies of the singular and plural past-tense forms, as these forms are realized identically. The verbs have past-tense frequencies between 0, for the verbs vlaggen 'hang out the flag' and dorsen 'to thresh', and 68311, for leggen 'to lay'. The verbs end in five different types of final obstruents: 35 verbs end in a bilabial plosive (P), 48 in an alveolar plosive (T), 41 in an alveolar fricative (S), 27 in a labiodental fricative (F), and 25 in a velar fricative (X).

A male speaker of Dutch, who systematically maintains the voiced/voiceless opposition for all plosives and fricatives, realized the plural present-tense forms of the verbs in phrases in which they were preceded by the pronoun wij [ʋɛi] 'we'. Examples of these phrases are [ʋɛi vrezən] wij vrezen 'we fear', [ʋɛi sxrɔbən] wij schrobben 'we scrub', and [ʋɛi jœyxən] wij juichen 'we cheer'. The phrases were recorded in a sound attenuated room by means of a DAT-recorder Aiwa HD S100 and a Sony microphone ECM MS957. The recordings were stored as .wav files (sample rate: 48 KHz) on a computer by means of the speech analysis package Praat (Boersma 1996). They were presented in one of eighteen random orders to the participants with two intervening breaks. These actual test phrases were preceded by 9

practice phrases and another break.

Procedure. An experimental trial consisted of a beep (500 ms, 377 Hz) followed by the test phrase over closed head-phones (Sony MDR-55). The participants' task was to decide as quickly and as accurately as possible whether the past-tense form corresponding to the presented present-tense form ends in [tən] te + n or [dən] de + n. The [n] following the past-tense suffixes indicates that the verb form is plural. The participants made their choices known by pressing the ten or den button. Half of the participants pressed the den button with their dominant hand, while the other half pressed the ten button with this hand. The time-out was set to 2500 ms. We presented the phrases auditorily in order to make sure that the participants took the whole word into account, and did not base their choice between ten and den just on the last grapheme of the verb stem. After the participants had pressed a button, they also wrote down the past-tense form. These written past-tense forms allow us to ascertain whether the participants had understood the presented verbs as intended, and had not understood, for instance, [ʋɛi ɣɪsən] wij gissen 'we guess' as [ʋɛi ɣɪstən] wij gisten 'we ferment'. The participants initiated the next trial by pressing the den button.

Since each participant pressed a button as well as wrote down his or her answer for every verb, we have four dependent variables, as already mentioned above. The first one is the suffix written down by the participant. The second variable represents the inconsistency errors, that is, the inconsistencies between the participants' written choices and the choices they made when pressing a button. The third variable represents the reaction times, and

the fourth variable the time-out errors.

Results and Discussion We discarded 14 trials in which the participants wrote down past-tense forms the stems of which do not correspond to the stems of the presented stimuli. For instance, we discarded the trial in which a participant wrote down wij schipten as the past-tense form of [ʋɛi sxɪmpən] wij schimpen, and the one in which a participant wrote down wij mistten as the past-tense form of [ʋɛi mɪsən] wij missen. The participants probably misunderstood the verbs in these trials. These 14 trials form less than 0.3% of all trials. In the analyses of the inconsistency errors and reaction times, we also discarded the 454 trials in which the participants produced time-out errors.

We start the discussion of our results with the analysis of the past-tense forms that the participants wrote down. These past-tense forms show the participants' final, and therefore best thought-out choices. For this analysis, we discarded another 14 trials in which the participants wrote down present-tense forms that are homophones with the requested past-tense forms. To give an example, we discarded wij boeten as response to [ʋɛi butən] wij boeten, which has wij boetten as its correct past-tense form. For these trials, we are not certain that the participants responded with a past-tense form. We merged all past tense forms of a verb that were written with te and ten. Similarly, we merged the responses written with de and den. The presence or absence of the grapheme n is irrelevant for our research question: As already mentioned above, the grapheme n just indicates that the number of the verb form is plural. We also merged the forms in which the stems were spelled correctly, and the forms in which the stems were spelled with a grapheme that reflected the wrong underlying

[voice]-specification for the final obstruent. For example, we merged <u>krabten</u> and <u>krapten</u>, as responses to [ʊɛi krɑbən] <u>wij krabben</u>. Both forms end in the non-standard suffix, since the final obstruent of <u>krab</u> is underlyingly voiced (/b/), and should therefore be followed by <u>de</u>. The form <u>krabten</u> shows the correct spelling of the verb stem, which equals the underlying form assumed in generative analyses, but it violates the spelling conventions of Dutch, according to which the stem-final grapheme <u>b</u> must be followed by the allomorph <u>de</u>. The form <u>krapten</u> does not show the correct spelling of the verb stem, since the stem-final obstruent is represented as underlyingly voiceless. One might argue that the participants writing down this form did not know that the stem-final obstruent was underlyingly voiced. However, the participants heard [krɑbən], in which the stem-final obstruent was realized as voiced, and they therefore could deduce from the signal that the stem-final obstruent was underlyingly voiced. We think that the participants wrote down <u>p</u> instead of <u>b</u>, simply because <u>p</u> is more in line with the Dutch spelling conventions than <u>b</u> before the allomorph <u>te</u>. We consequently retained in the data set responses such as <u>krapten</u>, in which the spelling of the stem-final obstruent reflects the wrong underlying [voice]-representation. These responses form less than 0.3% of all responses.

We analyzed the proportion of responses with non-standard past-tense suffixes using a logistic regression analysis. Note that we can only ascertain effects of analogy in the participants' written responses when they report a non-standard form. When they report a standard form and the phonological gang supports this form, we do not know whether this form has been retrieved from memory or whether it has been computed on-line. Since analogical models predict that participants should report more non-standard forms when

there is stronger analogical support for the non-standard suffix, we will gauge the effect of analogy by means of the absolute difference between what the standard form prescribes and what is favored by analogy. The standard form prescribes de with a probability of either 0 or 1. The analogical probability with which a verb takes de equals the proportion of words falling in the same phonological gang in Table 1 that end in a voiced obstruent. The absolute difference between these two probabilities will be referred to as the "prediction difference". This variable captures well the competition between standard form and the form supported by the analogical gangs, and we will therefore also use it in the analyses of the three other dependent variables. The verbs in our experiment have prediction differences between 0.000 (e.g., gapen 'to yawn', and hopen 'to hope') and 0.992 (e.g., juichen 'to cheer' and doven 'to extinguish').

In addition to prediction difference, we also took into consideration as independent variables the log frequency of the past-tense form (conflating the singular and plural past-tense frequencies), the type of the stem-final obstruent (P, T, S, F, X), the standard suffix (whether the standard prescribes te or de), and participant group ([+F], [-F], and [± F]).

A logistic regression analysis revealed significant main effects for all variables (prediction difference: $F(1, 526) = 154.83$, $p < 0.001$; log frequency of the past-tense form: $F(1, 524) = 66.30$, $p < 0.001$; the type of the stem-final obstruent: $F(4, 521) = 84.69$, $p < 0.001$; the standard suffix: $F(1, 520) = 19.46$, $p < 0.001$; and participant group; $F(2, 518) = 9.71$, $p < 0.001$). Participants created more non-standard past-tense forms for verbs with higher prediction differences, for verbs with lower-frequency past-tense forms, for verbs with stems ending in alveolar or labiodental fricatives, and for verbs for which the standard prescribes

de. The participants of the [± F] group, who unsystematically distinguish between voiced and voiceless fricatives, created more violations than the other participants. Given the small number of participants in this group (5), this main effect of group may not be reliable. Due to singularity in the data matrix, no interactions could be incorporated in the model.

The logistic regression model should be interpreted with caution, however, since the residuals of the model show considerable deviations from normality. We therefore also analyzed the proportion of non-standard past-tense forms by means of a (non-parametric) Classification And Regression Tree analysis (Breiman et al. 1984), with mincut set to 10. The resulting cross-validated pruned tree is shown in Figure 1a. The higher a partition is up in the tree, the more relevant it is. In addition, the vertical length of the branches reflects the relevance of the factors, that is, the explained "variance" (technically the reduction in node heterogeneity). The figure shows that the first branch or partition in the tree is based on the prediction difference. Further branches show that the type of the stem-final obstruent and the frequency of the past tense form are relevant. The type of obstruent is relevant in case the prediction difference is low: Larger numbers of non-standard forms are found in the case of stem-final alveolar fricatives and stem-final labiodental fricatives. When the prediction difference is high, the frequency of the past-tense forms of the verbs emerges as relevant: The lower the frequency of the past-tense form of a verb is, the more non-standard past-tense formations are reported. The regression tree presents no evidence for an effect of the standard suffix, nor for an effect of participant group. In conclusion, this analysis presents roughly the same picture as the logistic regression model.

The main effect of prediction difference challenges the rule-based account. This account

predicts no systematic effect of analogical gangs on the choices made by the participants, contrary to fact. In addition, the absence of a reliable effect for participant group provides further evidence against the rule-based account. Under the rule-based account, one would expect that the [-F] participants, who do not realize the difference between voiced and voiceless fricatives in their own speech, would show the largest effects of analogy. However, all participant groups emerge as very similar with respect to the effects of analogy. The effect of frequency is as expected: When the frequency of the standard form is low, the form supported by the phonological gangs meets less resistance from the standard form. The effect of the type of the final obstruent shows that participants produced more non-standard forms for words ending in alveolar and labiodental fricatives than for words ending in plosives or velar fricatives. This may stem from the Dutch spelling conventions, which prescribe that alveolar and labiodental fricatives are always spelled as voiceless before both te and de. This convention implies that the orthographic forms of stems ending in alveolar or labiodental fricatives do not provide any information about the past-tense allomorph required by the standard conventions. In the absence of this information, more non-standard forms are to be expected. Finally, the participants created more non-standard forms for verbs of which the standard past-tense forms end in de. This suggests that participants had a preference for te. There are two possible explanations for this preference. The first explanation is that most verbs ending in an obstruent take te in the standard forms, and the experiment, correspondingly, contains more verbs taking te (54%) than verbs taking de (46%). The participants had to press the ten button more often, and this may have induced a list effect favoring te. A second explanation builds on the observation that word-internal obstruent

clusters in Dutch tend to be voiceless in monomorphemic words (Zonneveld 1993). Speakers may generalize this regularity to morphologically complex words. They would then show a preference for te because obstruents followed by te create voiceless obstruent clusters, that is, obstruent clusters of the unmarked type.

INSERT FIGURE 1 ABOUT HERE

We now turn to the 152 inconsistency errors, that is, the trials in which the participants pressed the ten button but wrote down den, or vice versa. A logistic regression model showed main effects for all variables (prediction difference: F(1, 526) = 18.63, p < 0.001; log frequency of the past-tense form: F(1, 524) = 6.43, p = 0.01; type of the final obstruent: F(4, 521) = 20.75, p < 0.001; standard suffix: F(1, 520) = 10.14, p = 0.001; and participant group: F(2, 518) = 4.87, p = 0.008). The participants created more inconsistency errors for verbs with higher prediction differences, for verbs with lower-frequency past-tense forms, for verbs with stems ending in alveolar or labiodental fricatives, and for verbs for which the standard prescribes the suffix de. The model also revealed an interaction of the type of the stem-final obstruent by the standard suffix ($F(4, 513) = 10.20, p = 0.04$). The participants with a systematic distinction between underlyingly voiced and voiceless fricatives ([+F]) were the least consistent. However, this effect of participant group may be due to the small number of participants in the [±F] group (5). Removal of these five participants from the data set resulted in a model in which participant group is not significant ($p > 0.1$).

Unfortunately, the residuals of this logistic model are again not normally distributed, which implies that the model should be interpreted with caution. A Classification And Regression Tree analysis of the data indicates that the type of the stem-final obstruent and

the prediction difference are good predictors of the proportions of inconsistency errors. The pruned cross-validated classification tree is shown in Figure 1b. Verbs ending in alveolar or labiodental fricatives (right-hand branch of the tree) tend to cause more inconsistency errors than verbs ending in plosives or in velar fricatives (left-hand branch of the tree). In addition, verbs with a higher prediction difference cause more inconsistency errors than verbs with a lower prediction difference. The frequency of the past-tense form is a predictor as well, but only for a small subset of the data: Verbs ending in a plosive or a velar fricative that have a high prediction difference cause more inconsistency errors if their past-tense form is of a low frequency of occurrence (8.43%) than if it is of a high frequency (2.36%).

These analyses of the inconsistency errors support the conclusions reached on the basis of the proportions of non-standard forms.

We analyzed the reaction times for the trials leading to standard and non-standard forms jointly by means of Linear Mixed Effects (LME) models (Pinheiro & Bates 2000; Baayen, Tweedie & Schreuder 2002). An LME analysis of all these trials with log reaction time as dependent variable revealed main effects for prediction difference ($F(1, 6722) = 39.20, p < 0.0001$), frequency ($F(1, 6722) = 180.13, p < 0.0001$), type of final obstruent ($F(4, 6722) = 14.71, p < 0.0001$), standard suffix ($F(1, 6722) = 89.84, p < 0.0001$), and interactions of type of obstruent by prediction difference ($F(4, 6722) = 4.71, p = 0.0009$), and of type of obstruent by standard suffix ($F(4, 6722) = 3.63, p = 0.0059$). Participant group was not a significant predictor. The residuals of the model are normally distributed.

The random effects part of the LME model shows that there are individual differences between the participants with respect to their sensitivity to frequency and to type of ob-

struent (Log-likelihood ratio $= 138.41, p < 0.0001$). These differences are probably due to the differences in the individual mental lexicons of the participants: The participants do not know exactly the same words, and moreover have encountered the words that they do know different numbers of times. The phonological gangs and the strengths of the standard forms consequently vary somewhat across participants. The residual standard deviation of the model was 0.492.

In the LME regression model, the prediction difference has a significant and positive coefficient. This is exactly as predicted by an analogical account. If the prediction difference is larger, the analogy more strongly supports the non-standard suffix. Consequently, the competition between the standard and non-standard suffix is larger, leading to longer reaction times. Vice versa, if the prediction difference is smaller, the analogy more strongly supports the standard suffix, and the reaction times are shorter. The analogical sets listed in Table 1 clearly show gang effects.

Not surprisingly, the main effect of frequency is facilitatory. Present tense forms with higher frequencies are recognized faster than low frequency verb forms (Baayen, McQueen, Schreuder 2003). In addition, participants can start producing a past-tense form faster when the form is of a high frequency than when it is of a low frequency of occurrence (Oldfield & Wingfield 1965; Jescheniak & Levelt 1994).

The main effect of standard suffix shows that participants respond faster when they opt for the past-tense suffix te. This effect in the response latencies corresponds with the preference for te observed in the logistic regression analysis of the counts of non-standard responses and inconsistency errors. Note that the fast reaction times for te cannot be due

to the positions of the buttons with respect to the participants' dominant hands, since half of the participants pressed the ten button with their dominant hand, while the other half pressed the den button with this hand. (The position of the buttons with respect to the dominant hand did not emerge as significant when added to the LME model.)

The main effect of type of obstruent may in part be due to the orthographic conventions of Dutch, which, as explained above, differ for labiodental and alveolar fricatives compared to the other obstruents. We are uncertain on how to interpret the interaction of the type of obstruent by prediction difference. We suspect that prediction difference, as defined in terms of CART-derived probabilities, may not be sensitive enough to capture the full contributions of the different types of obstruents.

We also analyzed separately the trials leading to standard forms and the trials leading to non-standard forms. The analysis of the trials leading to standard forms show exactly the same main effects and the same interactions as the main analysis. The analysis of the trials leading to non-standard forms shows a main effect of the standard suffix ($F(1, 120) = 3.968, p = 0.0486$), and an interaction of frequency by type of final obstruent ($F(4, 120) = 3.927, p = 0.0050$). There are no main effects of prediction difference, frequency, and type of final obstruent, probably because most verbs leading to non-standard forms are of a high prediction difference, of a low frequency of occurrence, and end in alveolar or labiodental fricatives (see the analysis of the non-standard forms above). The interaction of frequency by type of final obstruent shows that frequency remains relevant also for these words.

These results from the LME analysis again argue against the rule-based account. The main effect of prediction difference shows that the effect of phonological gangs is pervasive,

instead of being restricted to occasional, random lapses in performance. It shows competition between the standard and non-standard forms, and it, therefore, indicates, furthermore, that memory-retrieval and analogical computation are not simply cascaded but operate in parallel.

Finally, we discuss the 454 time-out errors. We first analyzed the data with a stepwise logistic regression model, which revealed main effects for frequency ($F(1, 526) = 19.27, p < 0.0001$) and standard suffix ($F(1, 525) = 6.07, p < 0.0137$), as well as an interaction of standard suffix by prediction difference ($F(2, 523) = 4.94, p = 0.0072$). A higher frequency led to fewer time-out errors, and when the standard prescribes te, participants made fewer time-out errors than when the standard prescribes de. The interaction of standard by prediction difference also documents the previously observed preference for te: When the standard prescribes te, while the phonological gangs support de, participants produce more time-out errors than in the reverse situation. The residuals of this logistic models are again not normally distributed, and we also analyzed the time-out errors with a Classification And Regression Tree analysis. This analysis revealed only an effect for frequency (see Figure 1c).

3. General Discussion

This study addresses the question to what extent the production of regular past tense forms in Dutch is affected by analogical processes. Standard generative analyses view the suffixation of de or te to the verb stem as a completely regular process governed by the underlying [voice]-specification of the stem-final obstruent. We have pitted this rule-based account against an analogical account according to which the phonological similarity structure of the words in the lexicon affects the choice of the past-tense allomorph. The experiment reported

in the present study shows that analogical similarity indeed affects past-tense production across the board, even when participants produce standard forms, while having all relevant information to apply the rule at their disposal.

In our experiment, we presented plural present-tense forms to participants over head-phones, and asked them to produce the corresponding past-tense forms. In Dutch, past-tense forms are created by adding the suffix te(n) or de(n) to the verb stems. The participants' task was to press as quickly and as accurately as possible the ten or den button, and sub-sequently to write down the whole past-tense form. The experiment yielded four dependent variables: (1) the proportion of non-standard past-tense forms written down by the partic-ipants, (2) the inconsistency errors between the suffixes that the participants chose when pressing a button and the suffixes in the past-tense forms they wrote down, (3) the reaction times, and (4) the time-out errors.

We found that three dependent variables show a main effect of analogy: Participants cre-ated more non-standard past-tense forms, produced more inconsistency errors, and reacted more slowly for verbs with stronger analogical support for the non-standard allomorph.

These findings are problematic for the classic rule-based account for the following rea-sons. First, the rule-based account predicts that the analogical support for a non-standard allomorph should not affect normal past-tense production, contrary to fact. Second, under the rule-based account, one might expect that participants who do not produce a systematic difference between voiced and voiceless fricatives in their own speech might be more prone to fall back on analogical reasoning. However, there is no evidence in our data that this might be the case. Third, classic rule-based accounts stagger rule-based processes and analogical

fall-back procedures. In the framework of Anshen & Aronoff (1988), analogical processes are described as slow compared to rule-based processes, and rules should determine the outcome without interference from analogical processes. No competition is expected between the standard and non-standard allomorph, contrary to fact. In the dual route model of Pinker (1999), production proceeds by first attempting lexical look-up in an associative memory (where similarity effects might arise). Upon failure of this look-up, which is the normal situation for regular inflected forms, a symbolic rule is assumed to be started up. Again, this is an account that does not predict the observed competition between the standard and non-standard allomorphs.

One might argue that the present results are artificial and induced by the task. Although we cannot prove that this is not the case, we can point out that non-standard forms are not exceptional in Dutch. The transcription of 100 past-tense forms from the Corpus of spoken Dutch (CGN: Corpus Gesproken Nederlands, http://www.elis.rug.ac.be/cgn/index_nl.html) with strong analogical support for the non-standard suffix (prediction difference > 0.5) yielded, according to seven transcribers, at least four non-standard past-tense forms: eisde 'demanded'(r3nl_24/fn001389), deinste 'winced' (r3nl_20/fn001151), bonste 'banged' (r3nl_20-/fn001175), and vergisde 'was mistaken' (r3nl_19/fn001080). This simple survey shows that non-standard forms are not uncommon and that they are not restricted to written language.

We conclude that the traditional rule-based account cannot provide an insightful explanation of our data. However, there are several other theoretical frameworks that can incorporate these results. Stochastic Optimality Theory (Boersma 1998, henceforth SOT) is a linguistic framework in which probabilistic data can be handled (see, e.g., Manning 2003,

for a comparison of SOT with standard statistical approaches). In SOT, the phonological gangs as captured by CART can be re-conceptualized and mapped onto probabilistic violable constraints. Ernestus & Baayen (2003) show how SOT can be used to model the choice of the past-tense allomorphs for pseudo-verbs. In order to account for the production of past-tense forms of existing verbs, the competition between the standard form and the non-standard, as moderated by the similarity structure in the lexicon, has to be incorporated. This can probably be done by adding faithfulness constraints that demand faithfulness of the output with respect to the stored standard past-tense form. Given the observed effect of word frequency, the position of these faithfulness constraints in the constraint hierarchy should be made dependent on the frequency of the relevant individual past-tense forms. We do not see, however, how SOT might account for the inhibitory effect of the competition between the standard and non-standard forms on the reaction times.

Another linguistic framework in which the present data can be accounted for is the analogical approach exemplified by TiMBL and AML. These analogical models are very good at capturing the analogical support of phonological gangs for non-standard forms. However, the competition between the standard and non-standard form attested in our experimental data is not expected by these models as currently formulated. In TiMBL, if the standard form is in the lexicon, it will be retrieved and no analogical computations will take place. In AML, the presence of the standard form in the lexicon blocks the analogical force of the phonological gangs. AML does incorporate the possibility of imperfect memory (Skousen 1989), that is, standard forms may sometimes not be accessible, in which case analogical effects will emerge. However, even with imperfect memory, there is no competition between the standard and

non-standard forms. Both TiMBL and AML can easily be modified such that two (potentially conflicting) sources of evidence are taken into account: the frequency-weighted evidence stemming from the standard form, and the evidence residing in the similarity structure among the other forms in the lexicon.

Finally, the present data pose no problem for connectionist models either. In particular, the competition between the standard and non-standard alternatives follows naturally in this framework as the result of exposure to the standard form in combination with gang effects emerging as a consequence of partial similarities in the mapping between present and past-tense forms.

Various researchers have argued that language is inherently graded, non-deterministic, and probabilistic (e.g., Bybee 1985, 2001; Skousen 1989, 1993; Daelemans et al. 1994; Daelemans, Berck & Gillis 1995; Rumelhart & McClelland 1986; Plunkett & Juola 1999; Sandra, Frisson & Daems 1999; Eddington 2000; Plaut & Gonnerman 2000; Seidenberg & Gonnerman 2000; Ramscar 2002). The present data provide further evidence that this view is correct.

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Appendix

Material used in the experiment. Each word is followed by the logarithm of the frequency of its past-tense form + 1 (conflating the singular and plural forms), its prediction difference, the proportions of non-standard forms produced in Groups I (participants with a systematic distinction between underlyingly voiced and voiceless fricatives), II (participants without such a distinction), and III (intermediate participants), the proportions of inconsistency errors in Groups I, II, and III, the mean reaction times in ms for Groups I, II, and III, and the proportion of time-out errors for

Groups I, II, and III.

Verbs prescribed to be suffixed with <u>te</u>:

<u>blaffen</u> 'to bark' 5.56 0.0910 0.00 0.00 0.20 0.04 0.00 0.00 681 628 518 0.04 0.00 0.40;

<u>blaten</u> 'to bleat' 2.20 0.3720 0.00 0.00 0.20 0.00 0.00 0.00 708 778 872 0.04 0.00 0.20;

<u>blussen</u> 'to extinguish' 2.56 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 735 837 764 0.00 0.00 0.00;

<u>boeten</u> 'to suffer' 1.95 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 704 694 848 0.08 0.00 0.00;

<u>dansen</u> 'to dance' 6.77 0.3570 0.12 0.18 0.20 0.10 0.09 0.20 808 600 421 0.12 0.00 0.00;

<u>dopen</u> 'to sop' 4.71 0.0000 0.00 0.09 0.00 0.00 0.09 0.00 849 116 976 0.00 0.00 0.00;

<u>doppen</u> 'to shell' 2.08 0.1350 0.00 0.18 0.00 0.00 0.00 0.00 838 964 827 0.08 0.00 0.00;

<u>dorsen</u> 'to thresh' 0.00 0.1350 0.00 0.18 0.20 0.00 0.10 0.00 1148 973 885 0.08 0.09 0.00;

<u>eisen</u> 'to require' 6.58 0.7650 0.08 0.09 0.00 0.08 0.00 0.00 853 988 866 0.00 0.18 0.00;

<u>fronsen</u> 'to frown' 5.95 0.3570 0.50 0.82 0.60 0.13 0.00 0.20 927 592 717 0.04 0.00 0.00;

<u>gapen</u> 'to yawn' 5.09 0.0000 0.08 0.09 0.00 0.00 0.00 0.00 765 776 769 0.00 0.00 0.00;

<u>gissen</u> 'to guess' 2.40 0.1350 0.00 0.00 0.00 0.08 0.00 0.00 861 534 1215 0.00 0.20 0.00;

<u>glippen</u> 'to slip' 5.33 0.1350 0.00 0.00 0.00 0.04 0.09 0.00 736 1061 1055 0.04 0.00 0.00;

<u>grissen</u> 'to snatch' 4.98 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 825 624 1224 0.08 0.09 0.00;

<u>groeten</u> 'to greet' 6.15 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 699 614 486 0.00 0.00 0.00;

<u>happen</u> 'to bite' 4.96 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 759 83 681 0.00 0.00 0.00;

<u>haten</u> 'to hate' 6.35 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 605 666 768 0.00 0.00 0.00;

<u>heersen</u> 'to rule' 0.00 0.7650 0.04 0.18 0.20 0.10 0.10 0.00 811 613 794 0.09 0.09 0.00;

<u>heten</u> 'to be called' 7.77 37.20 0.00 0.00 0.00 0.00 0.00 605 449 532 0.00 0.09 0.00;

<u>hopen</u> 'to hope' 7.37 0.0000 0.04 0.00 0.00 0.04 0.09 0.00 729 923 1024 0.00 0.00 0.00;

<u>juichen</u> 'to cheer' 5.30 0.9920 0.21 0.36 0.75 0.09 0.00 0.00 604 824 808 0.08 0.00 0.25;

kapen 'to hijack' 2.30 0.0000 0.00 0.00 0.00 0.00 0.00 0.00 724 777 779 0.00 0.00 0.20;

klampen 'to cling' 5.25 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 859 655 899 0.00 0.00 0.00;

klappen 'to clap' 6.22 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 638 589 655 0.04 0.00 0.00;

klitten 'to get entangled' 2.40 13.50 0.00 0.00 0.00 0.00 0.00 714 539 841 0.08 0.00 0.00;

kloppen 'to knock' 7.30 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 643 686 561 0.00 0.00 0.00;

knappen 'to crack' 4.69 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 722 813 787 0.04 0.00 0.00;

knarsen 'to crunch' 4.62 0.1350 0.00 0.18 0.00 0.00 0.00 0.00 681 762 782 0.00 0.00 0.00;

knippen 'to cut' 6.11 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 657 731 796 0.04 0.00 0.00;

knopen 'to knot' 5.83 0.0000 0.00 0.00 0.00 0.00 0.09 0.00 652 64 903 0.00 0.00 0.00;

krassen 'to scratch' 4.75 0.1350 0.00 0.00 0.00 0.00 0.09 0.00 693 566 527 0.04 0.00 0.00;

krijsen 'to screech' 5.27 0.7650 0.12 0.00 0.20 0.05 0.00 0.00 738 747 865 0.08 0.09 0.20;

kruisen 'to cross' 5.50 0.7650 0.08 0.18 0.20 0.12 0.00 0.00 719 659 1098 0.00 0.00 0.00;

kuchen 'to cough' 5.29 0.9530 0.04 0.00 0.00 0.00 0.10 0.00 724 964 1256 0.00 0.00 0.00;

kussen 'to kiss' 7.22 0.1350 0.00 0.00 0.20 0.00 0.00 0.25 523 764 602 0.04 0.09 0.20;

lachen 'to laugh' 8.64 0.9530 0.04 0.00 0.00 0.00 0.00 0.00 606 845 384 0.00 0.09 0.20;

lassen 'to weld' 2.48 0.1350 0.04 0.09 0.20 0.04 0.00 0.00 731 692 913 0.04 0.09 0.00;

letten 'to pay attention' 6.59 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 712 528 599 0.04 0.09 0.00;

loensen 'to squint' 2.08 0.7650 0.54 0.55 0.60 0.05 0.00 0.20 1055 942 999 0.12 0.18 0.00;

lossen 'to discharge' 5.39 0.1350 0.08 0.00 0.40 0.04 0.00 0.00 688 813 88 0.04 0.20 0.00;

loten 'to draw lots' 0.69 37.20 0.00 0.00 0.00 0.00 0.00 0.00 857 603 849 0.08 0.00 0.00;

missen 'to miss' 6.65 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 611 695 506 0.00 0.00 0.00;

motten 'to have to' 4.90 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 1128 985 1198 0.04 0.18 0.00;

passen 'to fit' 7.08 0.1350 0.00 0.00 0.20 0.00 0.00 0.00 732 727 604 0.00 0.09 0.00;

persen 'to press' 5.30 0.1350 0.00 0.09 0.00 0.04 0.09 0.00 632 784 987 0.00 0.00 0.00;

piepen 'to squeak' 5.04 0.0000 0.00 0.00 0.00 0.04 0.00 0.00 685 526 96 0.00 0.00 0.00;

planten 'to plant' 5.09 0.3570 0.00 0.00 0.00 0.00 0.00 0.00 548 546 712 0.00 0.00 0.00;

pleiten 'to plead' 5.36 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 714 572 621 0.00 0.00 0.00;

ploffen 'to thud' 4.82 0.0910 0.08 0.09 0.40 0.08 0.09 0.25 713 713 1168 0.00 0.00 0.20;

pochen 'to boast' 3.43 0.9530 0.04 0.00 0.20 0.04 0.00 0.25 804 795 923 0.00 0.00 0.20;

poepen 'to shit' 2.64 0.0000 0.04 0.00 0.00 0.00 0.00 0.00 855 749 1268 0.04 0.00 0.00;

poffen 'to roast' 1.10 0.0910 0.00 0.09 0.40 0.00 0.09 0.00 781 910 881 0.04 0.00 0.00;

praten 'to talk' 7.57 0.3720 0.00 0.00 0.00 0.05 0.00 0.00 486 349 417 0.08 0.09 0.20;

putten 'to draw' 5.53 0.1350 0.00 0.00 0.00 0.04 0.00 0.00 551 675 653 0.00 0.00 0.00;

rapen 'to pick up' 0.00 0.0567 0.00 0.00 0.00 0.00 0.04 0.10 0 841 625 862 0.00 0.09 0.00;

reppen 'to scurry' 4.62 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 832 999 1332 0.00 0.00 0.00;

schatten 'to estimate' 5.96 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 628 54 729 0.04 0.09 0.00;

scheppen 'to create' 5.34 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 761 742 634 0.00 0.00 0.00;

schimpen 'to scoff' 2.64 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 868 935 122 0.09 0.00 0.00;

schoppen 'to kick' 5.99 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 601 772 637 0.00 0.09 0.00;

schorsen 'to suspend' 2.40 0.1350 0.00 0.09 0.00 0.05 0.00 0.00 880 664 798 0.00 0.09 0.00;

schrapen 'to scrape' 5.85 0.0000 0.00 0.00 0.00 0.00 0.00 0.00 647 691 921 0.00 0.00 0.20;

sissen 'to hiss' 5.95 0.1350 0.04 0.00 0.00 0.00 0.09 0.00 625 561 831 0.04 0.00 0.00;

slepen 'to drag' 6.31 0.0000 0.00 0.00 0.20 0.00 0.00 0.00 567 491 64 0.00 0.00 0.00;

slissen 'to lisp' 2.56 0.1350 0.00 0.00 0.00 0.04 0.00 0.00 665 644 736 0.04 0.00 0.20;

sloffen 'to shuffle' 4.72 0.0910 0.00 0.00 0.00 0.04 0.00 0.00 705 774 866 0.04 0.00 0.00;

slorpen 'to slurp' 1.61 0.1350 0.00 0.00 0.20 0.00 0.00 0.00 1211 1163 1486 0.08 0.09 0.20;

snappen 'understand' 5.16 13.50 0.00 0.00 0.00 0.00 0.00 0.00 688 549 639 0.00 0.00 0.00;

spatten 'to splash' 5.38 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 656 657 754 0.00 0.00 0.20;

spotten 'to mock' 5.10 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 571 527 766 0.04 0.00 0.00;

stampen 'to stamp' 5.32 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 837 943 928 0.00 0.18 0.00;

stappen 'to step' 8.10 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 765 536 1063 0.00 0.00 0.20;

starten 'to start' 5.76 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 847 658 638 0.04 0.00 0.00;

steppen 'to ride a scooter' 1.10 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 723 804 839 0.00 0.00 0.00;

stoppen 'to stop' 7.59 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 704 601 61 0.00 0.00 0.00;

storten 'to crash' 6.53 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 545 427 794 0.00 0.00 0.00;

stoten 'to thrust' 6.78 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 521 723 393 0.00 0.09 0.00;

stuiten 'to be stopped' 5.64 37.20 0.00 0.00 0.00 0.00 0.00 0.00 645 436 1044 0.04 0.00 0.00;

stunten 'to stunt' 0.00 0.3570 0.00 0.00 0.00 0.00 0.00 0.00 716 634 761 0.12 0.00 0.00;

stutten 'to prop' 1.79 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 634 556 836 0.04 0.00 0.00;

suffen 'to doze' 1.95 0.0910 0.04 0.09 0.40 0.00 0.00 0.00 954 967 978 0.00 0.00 0.00;

surfen 'to surf' 0.00 0.8750 0.25 0.36 0.20 0.10 0.09 0.00 933 884 1006 0.12 0.00 0.00;

trappen 'to kick' 6.13 0.1350 0.00 0.00 0.00 0.04 0.00 0.00 633 602 465 0.00 0.00 0.00;

uiten 'to utter' 5.77 37.20 0.00 0.00 0.00 0.00 0.00 0.00 652 496 855 0.04 0.09 0.00;

vatten 'to grasp' 6.44 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 674 654 53 0.00 0.00 0.00;

venten 'to hawk' 1.95 0.3570 0.00 0.00 0.00 0.00 0.00 0.00 773 799 784 0.00 0.00 0.00;

vissen 'to fish' 5.13 0.1350 0.04 0.00 0.00 0.00 0.00 0.00 699 838 801 0.00 0.09 0.00;

vitten 'to carp' 2.48 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 661 695 826 0.04 0.00 0.00;

vorsen 'to research' 1.61 0.1350 0.04 0.09 0.40 0.05 0.10 0.00 1011 1086 905 0.04 0.09 0.00;

walsen 'to waltz' 2.56 0.3570 0.29 0.55 0.60 0.08 0.00 0.00 965 905 736 0.00 0.09 0.00;

wassen 'to wash' 5.77 0.1350 0.00 0.00 0.20 0.00 0.00 0.00 679 739 712 0.00 0.00 0.00;

wensen 'to wish' 7.20 0.3570 0.08 0.09 0.40 0.04 0.09 0.20 792 817 1383 0.00 0.00 0.00;

wippen 'to hop' 5.57 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 677 927 1005 0.04 0.00 0.00;

zetten 'to put' 8.98 0.1350 0.00 0.00 0.00 0.00 0.00 0.00 689 853 784 0.08 0.09 0.00;

zweten 'to sweat' 5.01 0.3720 0.00 0.00 0.00 0.00 0.00 0.00 675 611 996 0.00 0.00 0.00;

zwiepen 'to bounce' 4.61 0.0000 0.00 0.09 0.00 0.00 0.00 0.00 754 732 731 0.08 0.00 0.00.

Verbs prescribed to be suffixed with de:

beven 'to shake' 6.08 0.0080 0.00 0.00 0.20 0.04 0.00 0.00 900 1002 804 0.04 0.00 0.00;

blieven 'to like' 2.08 0.2220 0.12 0.55 0.20 0.05 0.00 0.00 1158 119 1237 0.17 0.09 0.00;

blozen 'to bloom' 5.67 0.2350 0.04 0.18 0.00 0.09 0.09 0.00 987 896 754 0.04 0.00 0.00;

bonzen 'to bang' 5.45 0.6430 0.12 0.18 0.20 0.13 0.00 0.00 839 742 1061 0.04 0.00 0.00;

braden 'to roast' 2.77 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 783 741 920 0.04 0.00 0.00;

branden 'to fire' 6.84 0.6430 0.00 0.00 0.00 0.04 0.00 0.00 541 483 610 0.04 0.09 0.00;

deinzen 'to wince' 5.30 0.2350 0.04 0.18 0.00 0.04 0.00 0.00 873 809 664 0.04 0.18 0.00;

deugen 'to be no good' 4.83 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 638 712 620 0.04 0.00 0.00;

doven 'to extinghuish' 5.37 0.0080 0.08 0.00 0.20 0.00 0.00 0.00 706 901 1112 0.04 0.00 0.00;

draven 'to trot' 5.09 0.0080 0.00 0.09 0.00 0.00 0.00 0.00 847 873 784 0.00 0.00 0.00;

dreigen 'to threaten' 6.94 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 693 669 736 0.00 0.00 0.00;

drogen 'to dry' 5.32 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 724 835 993 0.04 0.00 0.00;

dubben 'to waver' 1.10 0.8650 0.29 0.45 0.40 0.14 0.09 0.00 1108 1146 1399 0.12 0.00 0.20;

duiden 'to point' 4.92 0.6280 0.00 0.00 0.00 0.00 0.09 0.00 767 721 432 0.00 0.00 0.20;

dulden 'to endure' 4.93 0.6430 0.00 0.00 0.00 0.00 0.00 0.00 652 458 645 0.00 0.00 0.40;

durven 'to dare' 7.75 0.1250 0.00 0.09 0.00 0.00 0.18 0.00 804 668 818 0.04 0.00 0.00;

glanzen 'to gleam' 5.90 0.6430 0.08 0.09 0.00 0.09 0.00 0.00 696 543 869 0.04 0.00 0.00;

grenzen 'to border' 4.82 0.6430 0.00 0.18 0.20 0.05 0.11 0.00 887 106 940 0.08 0.18 0.00;

grijnzen 'to grin' 6.73 0.2350 0.12 0.00 0.20 0.04 0.00 0.00 740 918 843 0.04 0.00 0.20;

hijgen 'to pant' 6.08 0.0080 0.04 0.09 0.20 0.13 0.00 0.00 849 777 1226 0.04 0.00 0.20;

hoeven 'to need to' 7.88 0.2220 0.04 0.18 0.00 0.00 0.00 0.00 871 961 883 0.04 0.00 0.00;

klagen 'to complain' 6.03 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 602 598 611 0.00 0.00 0.00;

kleden 'to dress' 6.30 0.6280 0.00 0.00 0.00 0.00 0.09 0.00 803 862 791 0.09 0.00 0.00;

kleven 'to stick' 5.37 0.0080 0.04 0.09 0.00 0.00 0.09 0.00 836 712 775 0.04 0.00 0.00;

kneden 'to knead' 4.29 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 786 607 771 0.09 0.00 0.00;

krabben 'to scratch' 5.68 0.8650 0.58 0.18 0.60 0.14 0.09 0.00 959 1081 1253 0.12 0.00 0.00;

laden 'to load' 4.83 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 885 697 700 1.00 0.09 0.00;

landen 'to land' 5.38 0.6430 0.00 0.00 0.00 0.00 0.00 0.00 686 483 584 0.04 0.00 0.00;

leggen 'to lay' 8.83 0.0470 0.00 0.00 0.00 0.00 0.00 0.00 662 737 817 0.00 0.00 0.00;

leiden 'to lead' 7.89 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 799 754 1109 0.04 0.00 0.20;

leven 'to live' 7.90 0.0080 0.00 0.00 0.00 0.04 0.00 0.00 587 584 738 0.00 0.00 0.00;

loven 'to praise' 3.53 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 811 662 813 0.08 0.09 0.00;

lozen 'to drain' 3.04 0.2350 0.12 0.09 0.00 0.04 0.00 0.00 896 761 867 0.04 0.18 0.00;

luiden 'to sound' 6.57 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 834 589 637 0.04 0.00 0.00;

melden 'to report' 6.40 0.6430 0.00 0.00 0.00 0.00 0.00 0.00 597 563 867 0.00 0.00 0.00;

peinzen 'to think 4.86 0.2350 0.04 0.09 0.40 0.09 0.09 0.00 801 956 661 0.04 0.00 0.20;

plagen 'to tease' 5.37 0.0080 0.00 0.00 0.00 0.04 0.09 0.00 703 811 566 0.00 0.00 0.00;

plegen 'to commit' 5.21 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 584 447 573 0.00 0.00 0.00;

plonzen 'to splash' 3.69 0.6430 0.29 0.27 0.60 0.08 0.00 0.20 916 871 867 0.00 0.00 0.00;

pluizen 'to give off fluff' 1.10 23.50 0.12 0.18 0.20 0.13 0.10 0.00 889 808 599 0.04 0.09 0.00;

pogen 'to try' 5.35 0.0080 0.04 0.00 0.00 0.09 0.00 0.00 829 786 591 0.04 0.18 0.00;

proeven 'to taste' 5.67 0.2220 0.00 0.18 0.00 0.04 0.09 0.00 760 911 809 0.00 0.00 0.00;

razen 'to rage' 5.36 0.2350 0.00 0.00 0.00 0.04 0.00 0.00 904 959 602 0.04 0.09 0.00;

redden 'to save' 6.60 0.8650 0.00 0.00 0.00 0.00 0.00 0.00 652 810 528 0.00 0.00 0.00;

reizen 'to travel' 6.02 0.2350 0.00 0.09 0.00 0.00 0.18 0.00 805 826 638 0.04 0.00 0.00;

roven 'to steal' 3.69 0.0080 0.04 0.00 0.00 0.04 0.00 0.00 846 918 735 0.04 0.00 0.00;

schaden 'to damage' 2.71 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 828 731 604 0.04 0.00 0.00;

scheiden 'to separate' 5.66 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 731 682 897 0.04 0.00 0.00;

schrobben 'to scrub' 3.14 0.8650 0.25 0.27 0.20 0.08 0.18 0.00 1108 1051 1168 0.00 0.00 0.00;

schroeven 'to screw' 4.70 0.2220 0.21 0.09 0.00 0.08 0.00 0.00 912 1053 628 0.00 0.00 0.20;

schudden 'to shake' 8.26 0.8650 0.00 0.00 0.00 0.00 0.00 0.00 794 521 744 0.04 0.00 0.00;

slagen 'to succeed' 7.11 0.0080 0.00 0.00 0.20 0.00 0.00 0.00 882 889 979 0.08 0.09 0.00;

smeden 'to forge' 3.61 0.6280 0.00 0.00 0.00 0.04 0.00 0.00 862 791 681 0.00 0.00 0.00;

smoezen 'to whisper' 2.48 0.2350 0.42 0.27 0.00 0.09 0.00 0.00 1095 927 818 0.08 0.00 0.00;

snoeven 'to swagger' 2.48 0.2220 0.12 0.18 0.20 0.10 0.00 0.00 992 1131 1700 0.17 0.00 0.00;

spugen 'to spit' 5.42 0.0080 0.08 0.36 0.00 0.08 0.00 0.00 946 1248 616 0.00 0.00 0.20;

stoven 'to stew' 1.39 0.0080 0.04 0.00 0.20 0.00 0.10 0.00 1171 1229 912 0.17 0.09 0.00;

streven 'to strive' 5.38 0.0080 0.04 0.00 0.00 0.00 0.00 0.00 903 849 1088 0.00 0.18 0.00;

tergen 'to provoke' 2.48 0.0470 0.00 0.00 0.00 0.00 0.00 0.00 706 841 776 0.04 0.09 0.00;

tobben 'to worry' 3.50 0.8650 0.38 0.27 0.40 0.13 0.09 0.00 1207 1208 1061 0.04 0.00 0.00;

troeven 'to trump' 1.39 0.2220 0.12 0.00 0.20 0.13 0.00 0.00 983 1375 924 0.04 0.18 0.00;

turven 'to tally' 1.10 0.1250 0.12 0.00 0.00 0.08 0.00 0.00 1042 1105 995 0.00 0.09 0.20;

vegen 'to sweep' 6.97 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 744 593 668 0.00 0.18 0.20;

vergen 'to demand' 5.08 0.0470 0.00 0.18 0.20 0.05 0.00 0.00 942 1218 887 0.08 0.00 0.00;

vlaggen 'to hang out the flag' 0.00 0.0470 0.00 0.09 0.00 0.04 0.10 0.00 994 960 722.40 0.00 0.009 0.00;

voeden 'to feed' 4.77 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 820 621 971 0.00 0.00 0.00;

voegen 'to join' 7.52 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 585 720 590 0.04 0.00 0.00;

volgen 'to follow' 8.30 0.0470 0.00 0.00 0.00 0.00 0.00 0.00 612 763 567 0.00 0.00 0.00;

vrezen 'to fear' 6.65 0.2350 0.08 0.00 0.00 0.05 0.00 0.00 868 701 552 0.08 0.09 0.00;

waden 'to wade' 4.42 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 774 582 1201 0.05 0.09 0.00;

wagen 'to risk' 6.07 0.0080 0.00 0.00 0.00 0.09 0.00 0.00 615 818 882 0.08 0.18 0.00;

wenden 'to turn' 7.31 0.6430 0.00 0.00 0.00 0.00 0.00 0.20 805 610 613 0.00 0.00 0.00;

wieden 'to weed' 1.95 0.6280 0.00 0.00 0.00 0.00 0.00 0.00 838 676 819 0.00 0.00 0.00;

wiegen 'to rock' 5.32 0.0080 0.08 0.00 0.00 0.05 0.09 0.00 795 791 668 0.08 0.00 0.00;

wuiven 'to wave' 6.36 0.0080 0.08 0.00 0.00 0.04 0.00 0.00 958 944 749 0.00 0.00 0.00;

zalven 'to anoint' 2.30 0.1250 0.08 0.09 0.00 0.00 0.00 0.00 691 677 918 0.12 0.00 0.00;

zeven 'to sieve' 1.10 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 814 920 688 0.04 0.00 0.00;

zogen 'to breastfeed' 2.30 0.0080 0.00 0.00 0.00 0.00 0.00 0.00 1106 843 961 0.29 0.00 0.40;

zorgen 'to take care' 7.12 0.0470 0.00 0.00 0.00 0.04 0.00 0.00 502 755 311 0.00 0.00 0.00;

zweven 'to float' 6.24 0.0080 0.04 0.09 0.00 0.00 0.00 0.00 746 804 739 0.09 0.09 0.00.

Analogical gangs	Probability of voicing
1. {εi, ɑu, œy, aː, eː, oː, øː, i, u} {-, j, l, m, n, r} {P}	0.000
2. {εi, ɑu, œy, aː, eː, oː, øː, i, u} {-, j, l, m, n, r} {T}	0.372
3. {εi, ɑu, œy, aː, eː, oː, øː, i, u} {-, j, l, m, n, r} {S}	0.755
4. {εi, ɑu, œy, aː, eː, oː, øː, i, u, ɑ, ε, ɪ, ɔ, ʏ, y} {f, k, p, s, t, x} {P, T, S}	0.019
5. {ɑ, ε, ɪ, ɔ, ʏ, y} {-, m, r} {P, T, S}	0.135
6. {ɑ, ε, ɪ, ɔ, ʏ, y} {l, n} {P, T, S}	0.357
7. {εi, ɑu, aː, eː, oː, øː, y} {-, j, l, r, m, n} {F, X}	0.992
8. {i, u} {-, m} {F}	0.778
9. {ɑ, ε, ɪ, ɔ, ʏ} {-, m} {F}	0.081
10. {ɑ, ε, ɪ, ɔ, ʏ, i, u} {l, r} {F}	0.775
11. {ɑ, ε, ɪ, ɔ, ʏ, i, u} {-, j, l, r, m, n} {X}	0.953

Table 1: Analogical gangs of phonologically similar words defined in terms of the segments of the final rhyme according to a CART analysis of Dutch monomorphemic stems (Ernestus & Baayen 2003).
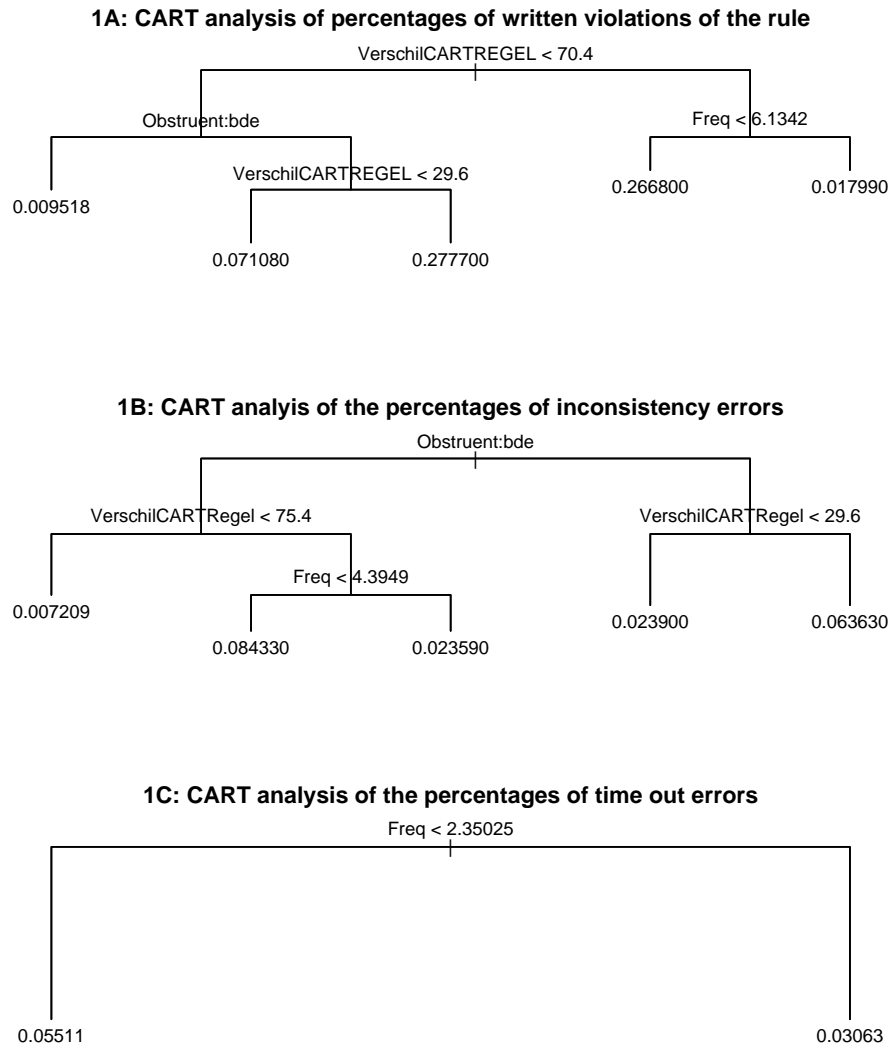
1A: CART analysis of percentages of written violations of the rule

VerschilCARTREGEL < 70.4

Obstruent:bde

VerschilCARTREGEL < 29.6

Freq < 6.1342

0.009518

0.071080   0.277700

0.266800   0.017990

1B: CART analyis of the percentages of inconsistency errors

Obstruent:bde

VerschilCARTRegel < 75.4

VerschilCARTRegel < 29.6

Freq < 4.3949

0.007209

0.084330   0.023590

0.023900   0.063630

1C: CART analysis of the percentages of time out errors

Freq < 2.35025

0.05511   0.03063

Figure 1: CART analyses of the proportion of rule violations, inconsistency errors, and time-out errors (PD: prediction difference; Freq: log (frequency + 1)).