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The impact of morphophonological patterns on verb production: evidence from acquired morphological impairment

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Abstract

Although much of the research on morphology and aphasia has focused specifically on the distinction between regular and irregular verb production, individuals with aphasia often present with differences in performance *within* these categories. While these within-category differences are relatively understudied, they have the potential to inform our understanding of the morphological processing system and treatment protocols for morphological impairment. The present study examines how morphophonological patterns in English impact past-tense production within the categories of regular and irregular verbs based on errors of an individual with acquired morphological impairment. Acquired morphological impairment was demonstrated by performance on two reading tasks. First, the individual produced more final consonant deletion errors in morphologically complex words (*prays*→[pre]) compared to homophones (*praise*→[pre]). Second, morphological deletion errors were found to occur at comparable rates for inflected regular verbs (*sinned*→*sin*) and inflected irregular verbs (*won*→*win*), whereas the analogous error (e.g. *ton*→*tin*) never occurred on the monomorphemic pairs. In order to examine differences within each category, we used a past-tense elicitation task designed to analyse the effect of differences in morphophonological pattern frequency on accuracy and error patterns in production. We found production of both regular and irregular verbs was affected by the extent to which different morphophonological patterns are supported in the language (i.e. the number of phonologically similar words within the lexicon which take the same inflectional change). These results provide evidence that morphophonological patterns are encoded in a way that impact morphological production, a finding which has both clinical and theoretical implications.

Keywords

Morphology; phonology; morphophonology; production; aphasia

Introduction

Impairment to morphological processing, and verb tense production in particular, is one of the hallmarks of non-fluent, agrammatic aphasia. Although this type of deficit can be a significant barrier to effective communication, relatively few systematic interventions exist

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compared to other deficits in aphasia (e.g. anomia, phonological impairment). In order to develop effective, evidence-based intervention for morphological impairment, a more complete understanding of the morphological processing system is needed. While there have been a number of studies examining verb tense impairment in aphasia, the majority focus on a single issue: comparing and contrasting performance on the regular and irregular English past-tense (e.g. Faroqi-Shah, 2007; Luzzatti, Mondini, & Semenza, 2001; Miozzo, 2003; Ullman et al., 1997, 2005; Weinrich, Boser, & McCall, 1999). This focus on regularity in the English past-tense is often motivated by a longstanding question in the psycholinguistic literature: Are regular and irregular verbs processed with the same underlying mechanisms or two separate mechanisms? While studies focusing on regularity-based dissociations in impairment (or lack thereof) have the potential to provide valuable insight into the mechanisms underlying morphological processing and answer important theoretical and clinical questions, this narrow focus may result in overlooking important factors that impact morphological processing *within* these categories. The current study investigates one such factor: the interaction of morphology and phonology in morphological impairment. Specifically, we ask whether the distribution of morphophonological patterns in the language impacts production in an individual with morphological impairment.

While many studies have focused on distinguishing between morphological and phonological contributions to morphological impairment (e.g. Badecker, 1997; Bird, Lambon Ralph, Seidenberg, McClelland, & Patterson, 2003; Faroqi-Shah, 2008; Faroqi-Shah & Thompson, 2004; Miceli, Capasso, & Caramazza, 2004; Szupica-Pyrzanowska, Obler, & Martohardjono, 2017), there is also evidence that morphological and phonological levels of processing interact with and influence one another. There have been reports of patients who demonstrate an increase in phonological errors in morphologically complex words compared to monomorphemic words (Kohn & Melvold, 2000), as well as evidence that phonological factors (e.g. the phonological complexity of affixes and stems) increase the prevalence of morphological errors (Obler, Harris, Meth, Centeno, & Mathews, 1999). In addition, there have been reports of patients who demonstrate a specific morphophonological impairment (i.e. an impairment that occurs at the interface of morphology and phonology; Cohen-Goldberg, Cholin, Miozzo, & Rapp, 2013; Shuster & Miozzo, 2017). In the current study, we examine the interaction of morphology and phonology in aphasia from a different angle. We ask whether the distribution of morphophonological patterns in the language (i.e. the number and proportion of phonologically similar verbs which take the same inflectional pattern, e.g. *find*→*found*; *grind*→*ground*, etc.) impacts past-tense production in an individual with an acquired morphological deficit.

The distribution of morphophonological patterns in English

Although irregular forms in the English past-tense are idiosyncratic by definition, many irregular inflectional patterns occur repeatedly in the language to varying degrees. Irregular past-tense forms range from those that are entirely anomalous (e.g. *do-did*) to those that have a semi-regular pattern repeated multiple times throughout the lexicon by phonologically similar words (e.g. *sleep-slept*; *weep-wept*; *sweep-swept*; etc., all of which share a rime both in their stem and inflected forms). One issue which has not been fully addressed in the

literature is what impact, if any, these morphophonological patterns and their distribution in the language have on morphological impairment. The majority of studies that investigate past-tense production in morphological impairment have focused on distinctions between irregular and regular verbs as cohesive groups without examining differences within these categories (e.g. Luzzatti et al., 2001; Miozzo, 2003; Ullman et al., 1997, 2005; Weinrich et al., 1999). Morphological impairment studies that examine morphophonological patterns beyond the regular/irregular distinction have generally examined very broad categories (e.g. comparing \pm vowel change and \pm affixation [Fix & Thompson, 2006] or comparing words from high and low-density morphophonological neighbourhoods [Harris & Humphreys, 2015]) as opposed to individual morphophonological patterns.

While the impact of morphophonological patterns on morphological impairment has not yet been investigated, research has suggested that these patterns play a role in how unimpaired individuals inflect novel words (Albright & Hayes, 2002; Albright, 2002; Albright & Hayes, 2003). In order to systematically investigate the impact of morphophonological patterns, Albright and Hayes (2003) created a computational learner (the Minimal Generalization Learner) which quantifies how prevalent different morphophonological patterns are in the lexicon. Given a stem-inflected pair (e.g. *ring-rang*) the learner calculates a “confidence score”, a quantified measure of how well that morphophonological pattern conforms to the overall morphophonological patterns of the language. In generating confidence scores, the learner takes into account not only how frequently a pattern is applied across phonologically similar verbs (e.g. *ring-rang*, *sing-sang*), but also the number of phonologically similar verbs which *do not* take the same transformation (e.g. *bring-brought*, *fling-flung*, etc.). The result is a number between 0 and 1 which reflects how well a stem-inflected pair fits the overall patterns of the lexicon, with 0 being the most anomalous and 1 fitting the patterns of the lexicon the most closely (for a more complete description of how the Minimal Generalization Learner calculates confidence scores, see Albright & Hayes, 2002; Albright & Hayes, 2003 as well as the Methods section of this study). Importantly, both regular and irregular past-tense forms can vary in how well they fit the morphophonological patterns of the lexicon. Even though all regular verbs have the same past-tense inflectional pattern (stem + ed), how well this fits the patterns of the language as a whole depends in part on the phonology of the stem. Compare, for example, *rush*→*rushed* and *bake*→*baked*, two regular verbs which take the same past-tense allomorph (stem + [t]). In English, all verbs ending in a voiceless fricative (i.e. [s], [ʃ], [f], or [θ]) are regular (Albright & Hayes, 2003); as such, a word like *rushed* fits extremely closely with the overall morphophonological patterns of the language. On the other hand, *bake* has several words in the lexicon which are phonologically similar, but take an irregular inflectional change (e.g. *take*→*took*, *make*→*made*, *shake*→*shook*, *wake*→*woke*) making *bake*→*baked* relatively more anomalous than *rush*→*rushed*.

Using confidence scores calculated by the Minimal Generalization Learner, studies have found that unimpaired speakers are sensitive to morphophonological patterns in the language in a way that impacts the inflection of novel words. In an inflected non-word judgment task, both regularly inflected (e.g. *fleep*→*flept*) and irregularly inflected (e.g. *bredge*→*bredged*) non-words were judged to be more acceptable when they more closely matched the overall morphophonological patterns of the language (i.e. had higher confidence scores; Albright &

Hayes, 2003). A similar pattern was found in a past-tense elicitation task using non-words; participants were more likely to produce past-tense forms that fit more closely with the morphophonological patterns of the language (Albright & Hayes, 2003). Together, these data suggest a systematic sensitivity to morphophonological patterns that impacts both regular and irregular words.

While the work of Albright and Hayes provides compelling evidence that morphophonological patterns play a role in morphological productivity (i.e. inflecting new or novel words), it has yet to be seen whether the distribution of morphophonological patterns in the language plays a role in the online production of real words. In the present study, we extend the current body of research by investigating whether morphophonological patterns are encoded in a way that impacts accuracy and error patterns in morphological impairment. First, we demonstrate the presence of a morphological impairment in an individual with aphasia (RMI). In order to establish the presence of a morphological deficit that is separable from phonological impairment, we designed two single-word reading tasks to decouple the effects of morphology and phonology in the past-tense production of regular verbs (Analysis 1) and irregular verbs (Analysis 2). We then investigate whether RMI's performance in a past-tense elicitation task is impacted by the distribution of morphophonological patterns in the language as quantified by Albright and Hayes' Minimal Generalization Learner.

Case report

RMI (born 1974) is a right-handed male, with a history of left middle cerebral artery cerebrovascular accidents (CVAs). RMI suffered several CVAs between 2001 and 2011; his language was most significantly affected by his second CVA occurring in 2003. Prior to his neurological injuries, RMI earned a Bachelor's degree and was working professionally in marketing. The experimental data reported in this paper were collected between March 2014 and December 2014. This study and the collection of informed consent were approved by New York University's Institutional Review Board.

RMI's production in spontaneous speech, reading, and writing is characterized by frequent semantic, phonological and morphological errors. In structured tasks, RMI's phonological errors include omissions, substitutions, and additions of phonemes. In spontaneous speech, phonological errors are less frequent and typically present as mild, infrequent sound distortions. RMI also presents with some disfluency (occasional pauses and hesitations) with normal prosody. Standardized language assessment was conducted using the *Western Aphasia Battery-Revised* (WAB-R; Kertesz, 2006). RMI's WAB-R classification corresponded to conduction aphasia with an aphasia quotient of 69.9. Attention, executive function, and visuospatial skills were all found to be within normal limits based on the Cognitive Linguistic Quick Test (CLQT; Helm-Estabrooks, 2001). Non-verbal semantic knowledge was assessed using the Pyramids and Palm Trees Test (PPT; Howard & Patterson, 1992), in which he scored within normal limits (49/52).

Because the single-word reading and elicitation tasks of the current study require phonological structure across morphological intact word perception and comprehension,

RMI's speech discrimination and auditory and written comprehension were evaluated. Auditory word comprehension was assessed via the Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2012) on which RMI received a raw score of 209 (standard score: 98), corresponding to the 45th percentile for his age range (within normal limits). Speech discrimination was assessed using the nonword and word minimal pair discrimination subtests of the Psycholinguistic Assessment of Language Processing in Aphasia (PALPA #1 and #2, respectively; Kay, Coltheart, & Lesser, 1992); RMI demonstrated 96% accuracy on both the non-word minimal pair discrimination task (same: 36/36; different: 33/36) and word minimal pair discrimination task (same: 33/36; different: 36/36), indicating relatively intact speech discrimination skills. Reading comprehension was assessed using the word-to-picture matching subtest of the PALPA (#48); RMI correctly identified a written word from a field of five pictures with 97.5% accuracy (39/40). Taken together, the results of these tests indicate that RMI presents with relatively intact perception and comprehension of auditory and written words.

Establishing a morphological deficit

Morphological errors comprise a significant portion of the errors in RMI's production across tasks. In the Screening Battery for Morphology from the Johns Hopkins University Dysgraphia Battery (Goodman & Caramazza, 1985) administered as a reading task, RMI demonstrated 30% accuracy (18/60 correct). Of the errors in this task, 52% (22/42) appeared to have a morphological locus. Specifically, 38% of errors (16/42) consisted of deletion (e.g. *closest*→*close*), substitution (e.g. *sailed*→*sailing*), or addition (e.g. *strain*→*strained*) of morphological affixes, resulting in a real word. An additional 14% of errors (6/42) included the deletion, substitution or addition of a morphological affix resulting in a nonword (e.g. *blackness*→*blackless*; *desireable*→*underdesired*). Morphological errors occurred across inflectional and derivational morphology, regular and irregular forms, and included both prefix and suffix errors.

RMI's morphological deficit is also apparent in his written production. In a writing-todictation task, RMI demonstrated 25% accuracy (41/163). Of these errors, 39% (47/122) were either morphological variants of the target (e.g. *written*→*wrote*; *looking*→*looked*) or apparent attempts at morphological errors that were misspelled (e.g. *pension*→*pesioners*; *disconnect*→*unconneted*). As in reading, RMI demonstrated a wide variety of morphological errors, including deletions (e.g. *mocking*→*mock*; *kept*→*keep*), substitutions (e.g. *settled*→*settles*; *eats*→*ate*), and additions (e.g. *rust*→*rusty*; *begin*→*began*).

Although the current study specifically focuses on RMI's production of past-tense verbs, morphological errors occur in other morphologically complex words as well, including plural nouns. In a picture-naming task containing line drawings of single and multiple objects, RMI named 77% of pictures accurately (48/62). Of his errors, 50% (7/14) were errors of number (i.e. producing a plural form for a single picture or vice versa). These errors occurred across both regular and irregular forms (e.g. *snakes*→*snake*; *foot*→*feet*).

Analysis 1: distinguishing morphological impairment from phonological impairment

The high proportion of morphological errors in RMI's production across tasks strongly suggests that he presents with a morphological impairment. However, because RMI also presents with a phonological deficit, it is important to establish that these errors stem from a morphological locus, as it is possible that by chance, phonological errors may produce words which are morphologically related to the target. For example, what presents as reduction of a morphologically complex form to its stem (e.g. *walked*→*walk*) may actually stem from coda simplification rather than a failure to apply a morphological affix. In Analysis 1, we systematically examine whether RMI presents with a morphological deficit over and above any effects of phonological impairment.

In order to decouple effects of morphological and phonological complexity and establish that RMI's morphological errors stem from a morphological locus, a single-word reading list was developed that orthogonally varied morphological complexity (monomorphemic [$n = 100$] vs. bimorphemic [$n = 100$]) and phonological complexity (singleton coda [$n = 106$] vs. coda cluster [$n = 94$]). Words were matched pairwise across morphological complexity to contain the same rime (e.g. *fold*–*rolled*). A subset of 54 homophone pairs varying in morphological complexity (e.g. *packed*–*pact*, *rows*–*rose*) was also included to more closely balance phonological structure across morphological contrasts (see Appendix 1 for full list of stimuli). RMI was administered this list as a single-word reading task three times over the course of four months, resulting in a total of 600 productions. Administration lists contained 50–75% control stimuli, and homophone pairs were never administered within the same session.

Incorrect responses were categorized into four error types: morphological (deletion, addition, or substitution of an affix; e.g. *poured*→*pour*); phonological (misproduction with 50% of target phonemes maintained; e.g. *minx*→*mix*); semantic (e.g. *toad*→*frog*); and “other” (all errors which did not fall under the previous three categories). In addition, incorrect responses across error types were classified into two groups: those that were characterized by a final consonant deletion (e.g. *rolled*→[*rol*]; *fold*→[*fol*]), and all other error types. Final consonant deletion was chosen for analysis because it can be indicative of morphological or phonological simplification. Examining rates of final consonant deletion across levels of morphological complexity in rime-matched words and homophones provides insight into whether RMI's errors stem from a primarily phonological or morphological locus. If his errors primarily reflect phonological simplification, it would be expected that final consonant deletion would occur at similar rates across morphological complexity (e.g. *packed*→ [pæk] ≈ *pact*→ [pæk]). If his errors reflect morphological simplification, final consonant deletion would be expected to occur more frequently in morphologically complex words (e.g. *packed*→ [pæk] > *pact*→ [pæk]).

For reliability purposes, a second listener reviewed audio recordings of the sessions and transcribed 33% ($n = 200/600$) of the reported stimuli. On the judgment of correct versus incorrect whole word responses, there was 97% ($n = 195/200$) agreement between the first and second listener. Agreement between listeners regarding error type was 97% ($n = 122/126$). Discrepancies between listeners were typically the result of imprecise articulation at

the single phoneme level. For items that were not agreed upon, the first author reviewed the audio recording and made a final judgment.

Mixed-effects logistic regression models (Baayen, 2008; Jaeger, 2008) were used for all analyses in this study. Mixed-effects models were chosen as they are able to account for the impact of random (i.e. non-repeatable) effects. Specifically, we included day-to-day variation in performance (accounted for by the inclusion of session date as a random intercept) as well as random variation across individual items (i.e. variation not accounted for by any of the included fixed effects). Data were analysed using the `glmer` function in the `lme4` package (Bates, Machler, Bolker, & Walker, 2015) of R (R Core Team, 2016).

For Analysis 1, two separate mixed-effects logistic regression models were used to analyse accuracy of response (binary: correct vs. incorrect) and error type (binary: final consonant deletion vs. other error). For both models, morphological complexity (binary: monomorphemic vs. bimorphemic), phonological complexity (binary: singleton coda vs. cluster coda), and the interaction between morphological and phonological complexity were included as fixed effects. In addition, the following fixed effects were included to control for factors that may influence production: lexical frequency, order of administration (i.e. whether it was the first, second, or third time the given word had been administered), orthographic length, and orthographic neighbourhood size. Random intercepts for item and session date were also included.

For all models in this study, an initial model summary was run. For any fixed effect that was not significant according to the model summary, a chi-squared likelihood ratio test was conducted between the full model and a reduced model with the given variable removed. Fixed effects that did not significantly contribute to the model based on these model comparisons were excluded from the model. A reduced model was fit using only the fixed effects found to be significant contributors.

Analysis 1a: accuracy

RMI had an overall accuracy rate of 35% ($n = 211/600$). Of his incorrect responses, morphological errors were the most frequent error type (Table 1). Based on the reduced model summary¹ (Table 2) morphological status was found to be a significant predictor of response accuracy, such that morphologically complex words were more likely to be read incorrectly than monomorphemic words (Table 3). Morphological complexity remained a significant predictor of response accuracy when homophone and non-homophone subsets were analysed separately. Phonological complexity was also found to be a significant predictor of accuracy, such that words with phonologically complex codas were more vulnerable to error than those with singleton codas (Table 3). However, morphological complexity had a larger effect on RMI's performance.

¹ β coefficients indicate the change in the likelihood of a correct response based on the fixed effect. Negative coefficients indicate a decreased likelihood of a correct response (e.g. words which were morphologically complex were more likely to be produced correctly than morphologically simple words) while positive coefficients indicate an increase in likelihood of a correct response (e.g. words with higher frequency were more likely to be correct).

Analysis 1b: error type (final consonant deletion)

In addition to accuracy, RMI's error patterns were analysed. Specifically, we analysed the proportion of errors of final consonant deletion relative to other errors. Nearly half of RMI's errors were final consonant deletion (47% of total errors [182/389]). Based on the reduced-model summary (Table 4), morphological status was found to be a significant predictor of final consonant deletion, such that morphologically complex words were more likely to have errors of final consonant deletion than monomorphemic words (Table 5). Morphological complexity remained a significant predictor of final consonant deletion when homophone and non-homophone subsets were analysed separately. Phonological complexity of the coda (singleton vs. cluster coda) was also found to be a significant predictor of final consonant deletion, such that words with cluster codas were more likely to have errors of final consonant deletion than words with singleton codas (Table 5). As with accuracy, morphological complexity had a larger effect on RMI's rate of final consonant deletion than phonological complexity.

The results of Analysis 1 demonstrate that RMI's production is significantly impacted by morphological impairment. In a single-word reading task in which morphological and phonological complexity were orthogonally varied, RMI's production was significantly affected by morphological complexity; in rime-matched and homophone pairs which varied in morphological complexity, RMI was significantly more accurate in his production of monomorphemic targets than multimorphemic targets. This was true for words with both singleton and cluster codas. It was also found that morphological status was a significant predictor of RMI's rate of final consonant deletion, such that final consonants were deleted significantly more frequently in multimorphemic targets (e.g. *packed*→*pack*) than in monomorphemic targets (e.g. *pact*→[*pæk*]). In addition, nearly half of RMI's total errors were morphological. Importantly, these did not only consist of morphological simplification, but involved a range of morphological errors including errors of addition (e.g. *amaze*→*amazing*), errors of substitution (e.g. *cries*→*cried*), and derivational morphology (e.g. *absence*→*absent*). Taken together, these results indicate that RMI has a morphological deficit that impacts both his accuracy and error patterns.

Analysis 2: morphological errors across regular and irregular verbs

Analysis 1 established that RMI's production is significantly impacted by morphological impairment, separable from phonological errors. However, Analysis 1 only included regular inflections (plural or first person singular *-s* and past tense *-ed*) in order to maintain rime matches and homophone status across morphological status. As the distribution of morphophonological patterns in the language has been shown to impact the inflection of both regular and irregular novel past-tense forms (Albright & Hayes, 2003), it is important to determine whether RMI's morphological deficit affects both regular and irregular verbs before assessing the impact of morphophonological pattern distribution on his production. To this end, we investigated whether RMI's morphological impairment also impacts his production of irregular past-tense verbs.

We developed a single-word reading list designed to compare performance on regular and irregular past-tense verbs. Six types of stimuli were included: stem and inflected forms of

regular verbs (e.g. *sin–sinned*); stem and inflected forms of irregular verbs, pairwise matched to the rimes of the regular stems (e.g. *win–won*); and monomorphemic phonological control words, (i.e. two words pairwise matched to the rime of the stem and inflected irregular verbs, but with no morphological relationship to one another [e.g. *tin–ton*]) (Table 6; see Appendix 2 for complete list of stimuli). All pairwise rime matches were matched both phonologically and orthographically. RMI was administered this list as a single-word reading task three times over the course of four months, resulting in a total of 576 productions. The stimuli were broken into three different administration lists; stem-inflected pairs were never included within the same administration list, and only one list was administered per session. For reliability purposes, a second listener reviewed audio recordings of the sessions and transcribed 33% (192/576) of the reported stimuli. On the judgment of correct versus incorrect whole-word responses, there was 98% (189/192) agreement between the first and second listener, and agreement between listeners regarding relevant error type was 98% (81/83). For items that were not agreed upon, the first author reviewed the audio recording and made a final judgment.

We investigated how stimulus type (i.e. regular verb, irregular verb, or control) and inflectional status (i.e. stem vs. inflected form) and their interaction affect RMI's production accuracy. In order to further explore the distinction between morphological and phonological errors demonstrated in Analysis 1, we also examined RMI's error patterns. Specifically, we analysed the proportion of errors which reduce inflected forms to their stems (e.g. *sinned*→*sin*, *won*→*win*), or, in the case of the control words, the analogous phonological error (e.g. *ton*→*tin*). Given the structure of the stimuli, this particular error pattern allows us to most closely differentiate between phonological and morphological errors, while determining whether RMI's morphological deficit extends to irregular forms. A reduction from stem to inflected form has the same morphological shift for both regular and irregular verbs, but differs in its phonology. Conversely, the analogous error in the control stimuli (e.g. *tin*→*ton*) has the same phonological shift as the irregular verb reduction, but does not contain any morphological shift. If RMI produced similar rates of inflected→stem reduction for regular and irregular verbs, but not for controls, it would provide further evidence that RMI's errors are rooted in morphology, and demonstrate that this deficit affects both regular and irregular verbs.

The data were analysed using two mixed-effects, logistic regression models: one analyzing accuracy of response (binary: correct vs. incorrect), and one analysing error type (binary: inflected→stem reduction [e.g. *sinned*→*sin*, *won*→*win*, *ton*→*tin*] vs. other errors). For both models, stimulus type (regular verb, irregular verb, control), inflectional status (stem vs. inflected), and their interaction were included as fixed effects. Lexical frequency, order of administration (i.e. whether it is the first, second or third time RMI has seen a word), orthographic length, and orthographic neighbourhood size were also included as fixed effects. Random intercepts for item and session date were also included in each model.

Analysis 2a: accuracy

Overall, RMI was more accurate at producing stems than inflected forms (see Table 7). He exhibited similar rates of accuracy for stems of all stimulus types. However, accuracy

differed across stimulus types for inflected forms, with controls being the most accurate, and regular inflected forms the least accurate. Based on model comparisons, the interaction between inflectional status and stimulus type (regular verb, irregular verb, or control) was found to be a significant predictor of response accuracy, indicating that the effect of inflectional status on the likelihood of a correct response was modulated by stimulus type. Further testing indicated that this interaction was significant when comparing both regular and irregular verbs to controls; conversely the interaction was not significant when comparing regular and irregular verbs to one another (Table 8).

Analysis 2b: error type

RMI made a variety of errors across stimulus types and inflectional status. Across stimuli, phonological and morphological errors occurred at similar rates (40% [103/255] and 38% [97/255], respectively), with semantic errors comprising a smaller proportion of errors (3% [8/255]). However, these error types varied based on stimulus type and inflectional status, with morphological errors occurring much more frequently in regular and irregular inflected verbs relative to other stimuli (63% of errors for both regular [48/76] and irregular [36/57] verbs, compared to 4% [1/28] of control items). The majority of morphological errors across stimuli were errors of deletion (71% [69/97]), with errors of addition (13% [13/97]), substitution (9% [9/97]) and derivation (5% [5/97]) also occurring. There was also a single occurrence of regularization (*spun*→*spinned*).

RMI's rate of inflected-to-stem reduction was analysed across stimulus types (Table 9). Similar rates of reduction were found for regular and irregular verbs, with the analogous phonological error never occurring in controls. Logistic regression analysis indicated that there was no significant difference between regular and irregular verbs in likelihood of errors of inflected-to-stem reduction ($\beta = 0.176$, $z = 0.501$, $p = 0.617$).

The results of Analysis 2 provide additional evidence that RMI's production is significantly impacted by a morphological impairment that impacts his production of both regular and irregular past-tense verbs. In a single-word reading task containing stems and inflected forms of regular verbs (e.g. *sin*–*sinned*); stem and inflected forms of irregular verbs, pairwise matched to the rimes of the regular stems (e.g. *win*–*won*); and monomorphemic phonological control words, (e.g. *tin*–*ton*), RMI was more accurate in producing stems than inflected forms. Morphological errors of all types occurred at similar rates in regular and irregular verbs. Specifically, RMI reduced inflected forms to stems at similar rates for both regular and irregular forms (e.g. *sinned*→*sin*; *won*→*win*), while the analogous phonological error for control items (e.g. *ton*→*tin*) never occurred.

Analysis 3: the role of morphophonological distributions in past-tense production

Taken together, the results of Analyses 1 and 2 demonstrate that RMI's production is significantly affected by a morphological deficit, separable from phonological error, which impacts his production of both regular and irregular past-tense verbs. We followed these analyses with a past-tense elicitation task designed to examine the impact of morphophonological patterns in the language on RMI's accuracy and error patterns.

Research has provided evidence that the distribution of morphophonological patterns in the language plays a role in the inflection of both regular and irregular novel verbs (Albright & Hayes, 2002; Albright, 2002; Albright & Hayes, 2003). However the role morphophonological distributions play in the production of known words remains unclear. In the present study, we examine whether the distribution of morphophonological patterns in the language impacts RMI's production of regular and irregular past-tense verbs.

As outlined in the introduction, Albright and Hayes (2003) Minimal Generalization Learner quantifies how well different inflectional patterns fit the overall morphophonological patterns in the language. Albright and Hayes characterized each morphophonological transformation as a phonological change, and a context within which that change occurs (e.g. for *bleed-bled*, *lead-led*, *read-read*, *feed-fed*, etc., $i \rightarrow \mathcal{E}/[X_d_{[+PAST]}]$ [a change from /i/to/ \mathcal{E} /, preceded by any phoneme (denoted as free variable X) and followed by /d/]). The Minimal Generalization Learner calculates a "confidence score" for a given stem-inflected pair by dividing the number of words in the lexicon which fit the phonological constraints of the pattern (the "scope" of the pattern; e.g. in the example above, the number of stems in the lexicon that include [Xid], including words which do not have the same inflectional change, e.g. *heed-heeded*) by the number of words to which it actually applies (the number of "hits"; e.g. the number of words in the scope which actually take the given inflectional change $i \rightarrow \mathcal{E}$). This number is then adjusted based on the size of the scope relative to the lexicon, so that rules based on a smaller number of items receive a lower confidence score than those based on a larger set of items. The result is a number between 0 and 1 which represents how well a morphophonological pattern fits with the overall patterns of the lexicon (with 0 the most anomalous and 1 the closest fit). (For a full description of the Minimal Generalization Learner and the computation of confidence scores, see Albright & Hayes, 2002; Albright & Hayes, 2003)

In addition to generating a confidence score for the correct inflection of a verb, the Minimal Generalization Learner also generates confidence scores reflecting the likelihood of the application of other rules that could feasibly apply to the verb given the phonology of the stem and the morphophonological distributions of the lexicon. For example, when provided with the stem *bring*, the learner not only generates a confidence score for *brought*, but also for *bringed*, *brang*, and *brung*. The possible forms generated by the learner for each verb vary; however, because the addition of -ed is the most frequent rule in the language and occurs over such a wide range of phonology, the regularized form is generated for every verb. Although this rule is considered possible for all stems, the likelihood of its application (i.e. its confidence score) varies based on the number and proportion of phonologically similar verbs in the lexicon which actually take the regular inflection. For example, the confidence score for *catch* \rightarrow *caught* (0.986) is higher than the score for *find* \rightarrow *finded* (0.850) since *catch* has a higher proportion of phonologically similar verbs which actually take the regular past-tense inflection.

Confidence score is our predictor variable of interest in this study. Specifically, we predict that the confidence score for the correct inflection of a verb (e.g. *dig* \rightarrow *dug*, *walk* \rightarrow *walked*) will impact RMI's accuracy, such that words whose inflectional patterns are more strongly supported in the lexicon (i.e. those with higher confidence scores) will be less vulnerable to

error. In addition we predict that RMI's error pattern will be impacted by the confidence scores for *incorrect* inflections; within incorrect productions of irregular verbs, we predict that RMI's rate of regularization (e.g. *dig*→*digged*) will be impacted by the confidence scores for those forms (e.g. the confidence score for *dig*→*digged*, rather than the score for *dig*→*dug*).

Stimuli and task

RMI was administered a past-tense elicitation task including 99 regular verbs and 94 irregular verbs (see Appendix 3 for complete list of stimuli). These verbs represent a wide range of confidence scores, with values ranging from 0.00 to 0.99 (irregular verbs: range = 0.00–0.786, median = 0.570, mean = 0.467, sd = 0.266; regular verbs: range = 0.850–0.997, median = 0.970, mean = 0.963, sd = 0.032). Verbs with an identical stem and inflected form (e.g. *cut*, *hit*) were not included in the stimuli, as it is impossible to distinguish between a repetition of the stem and a correctly produced past-tense inflection. In addition, as RMI produces occasional voicing errors in spontaneous speech, verbs in which the sole irregular feature is inflectional devoicing (e.g. *burn*→*burnt*) were not included.

Verbs were presented in the context of a sentence frame, using a format based on that of Ullman et al. (1997); Ullman et al. (2005)), for example: *Every day I run a mile. Just like every day, yesterday I a mile.* Verb stems were followed by a two-word complement or adjunct to provide semantic context (e.g. *run a mile*). All trials included the same carrier phrases (“Every day I . Just like every day, yesterday I .”), with the target verb and complement/adjunct varying across stimuli. Sentence frames were presented verbally and visually to ensure comprehension: RMI was presented with a sheet containing a single printed sentence frame, which the presenter read aloud with appropriate intonation to elicit the inflected verb. RMI responded by verbally producing the inflected form of the given verb; his first full response to each item was recorded. The full list of stimuli was administered four times over the course of six months (with approximately 75 sentences presented per session), resulting in a total of 788 verb productions. Regular and irregular verbs were intermixed and order was randomized for each session. All sessions were recorded, and transcription verification was conducted off line. For reliability purposes, a second listener reviewed audio recordings of the sessions and transcribed 27% (206/768) of the reported stimuli. On the judgment of correct versus incorrect whole-word responses, there was 93% (203/206) agreement between the first and second listener, and agreement between listeners regarding relevant error type was 88% (98/108). For items that were not agreed upon, the first author reviewed the audio recording and made a final judgment. Incorrect responses were categorized into seven error types: stem maintenance (repetition of the given stem, e.g. *dig*→*dig*); regularization (addition of regular affix to irregular stem, e.g. *dig*→*digged*); suffixed irregular (e.g. *dig*→*dugged*); irregularization (phonological change that mirrors inflection of an irregular verb, e.g. *greet*→[gret]); other morphological error (e.g. *dig*→*digging*); stem error (word or non-word) with regular affixation (e.g. *run*→*walked*); and “other” (all errors which did not fall under the previous categories).

We first investigated the effect of morphophonological distribution on RMI's accuracy in production. Since confidence score (our primary variable of interest) is highly correlated

with regularity, we analysed regular and irregular verbs separately to better assess gradient differences in production based on confidence score. However, for both groups, it is predicted that accuracy will be impacted by morphophonological pattern, such that words with higher confidence scores (i.e. those that fit the patterns of the overall language the most closely) will be less vulnerable to error.

In addition to examining RMI's accuracy, we also analysed RMI's error pattern for irregular verbs. Specifically, we investigated whether confidence score impacted the rate at which RMI produced errors of regularization (e.g. *dig*→*digged*). However, rather than using the confidence score of the correct irregular inflection (e.g. *dig*→*dug*), we used the confidence score for the regularization error (i.e. how likely the regular rule [e.g. *dig*→*digged*] is to be applied to a given verb). If morphophonological distribution in the language does impact production, this effect may be observed even in the case of incorrectly produced targets. In the event that RMI is not able to correctly produce a past-tense irregular target, it is possible that the relative strength of competing inflectional patterns may impact the type of error he makes. In our analysis, we investigate whether the strength of the regular past-tense change (i.e. how likely a given verb is to be regularized based on the phonology of the stem) may modulate how frequently errors of regularization occur.

Data analysis

Data were analysed using mixed-effects, logistic regression models. Three different models were constructed, each with different dependent variables and data subsets: (1) regular verbs, accuracy (binary: correct vs. incorrect), (2) irregular verbs, accuracy (binary: correct vs. incorrect), and 3) irregular verbs, regularization errors (binary: regularization [e.g. *dig*→*digged*] vs. other error types).

Confidence score (calculated using the Minimal Generalization Learner; Albright & Hayes, 2003) was included as a fixed effect for all models. Because confidence score is a proportion variable bound by 0 and 1, a logit transformation was performed prior to analyses. In addition, the following fixed effects were included to control for factors which may influence production: lexical frequency (lemma frequency; CELEX; Baayen, Piepenbrock, & Gulikers, 1995), order of administration (i.e. whether it is the first, second, third or fourth time RMI has seen a word), phonological neighbourhood density, and number of phonemes in the inflected form. Models also included random intercepts for item and session date to account for random variation across individual items and day-to-day performance variation beyond that accounted for by order of administration.

Analysis 3a: accuracy (regular verbs)

RMI produced the correct past-tense form on 68% (269/396) of trials for regular verbs. Of his incorrect responses, stem maintenance was his most frequent error type (53% of errors [67/127]), with errors of irregularization (i.e. internal vowel change), regularly affixed stem errors (e.g. *walk*→*jogged*), and other morphological affixations (e.g. *walk*→*walking*) also occurring (Table 10).

A model was fit to analyse the effect of stimulus properties on accuracy for regular verbs.² Based on the reduced-model summary (Table 11), confidence score was found to be a

significant predictor of response accuracy, such that words with lower confidence scores (i.e. those that are more anomalous) were more vulnerable to error (mean confidence score for correct responses: 0.971; mean confidence score for incorrect responses: 0.946). Number of phonemes was also found to be a significant predictor of response accuracy.

Analysis 3b: accuracy (irregular verbs)

RMI produced the correct past-tense form on 33% (124/376) of trials for irregular verbs. A model was fit to analyse the effect of stimulus properties on response accuracy for irregular verbs. Based on model comparisons, only phonological neighbourhood size was found to be a significant predictor of accuracy ($p < 0.05$; Table 12), such that words belonging to larger phonological neighbourhoods were less vulnerable to error.

Analysis 3c: regularization errors (irregular verbs)

Of RMI's incorrect responses, errors of regularization (e.g. *dig*→*digged*) were the most frequent error type (49% of errors [124/252]), with errors of stem maintenance, irregularization (i.e. internal vowel change), suffixed irregular (e.g. *freeze*→*frozed*), regularly affixed stem errors (e.g. *run*→*walked*), and other morphological affixations also occurring (Table 10).

As previously mentioned, in addition to generating the confidence score for the correct inflectional pattern of a verb, the Minimal Generalization Learner generates confidence scores for other feasible rules based on the morphophonological distributions in the language and the phonology of the stem. In this analysis, rather than using the confidence score for the correct inflectional rule (e.g. *dig*→*dug*), we used the confidence score that reflects the likelihood of an incorrect regularization (e.g. *dig*→*digged*) for the given verb.

A model was fit to analyse the effect of stimulus properties on the likelihood of regularization errors for a subset of the data containing incorrect productions of irregular verbs.³ Based on the reduced-model summary, confidence score of regularization (e.g. the score for *dig*→*digged*) was found to be a significant predictor of rate of regularization ($\beta = 1.895$, $z = 4.563$, $p < 0.001$). Words with higher confidence scores for regularization (i.e. those with more support for the regular rule) were more likely to be regularized than those with lower scores (mean confidence score for regularizations: 0.954; mean confidence score for all other errors: 0.915). No other significant predictors of regularization were found.

The results of Analysis 3 demonstrate that RMI's production is significantly impacted by morphophonological distributions in the language (as represented by confidence score). For regular verbs, confidence score was found to significantly impact accuracy, such that words with lower confidence scores (i.e. those with less lexical support for their morphophonological rules) were more vulnerable to error. For irregular verbs, RMI's error pattern was significantly impacted by confidence score in that the confidence score for

²Model comparisons indicated that order of administration and lexical frequency did not significantly contribute to the fit of the model ($p > 0.05$). These variables were subsequently excluded from analysis.

³Based on model comparisons, order, frequency, phonological neighbourhood size, and number of phonemes were found to not significantly add to the model, and were subsequently excluded from analysis.

regularization (e.g. *dig*→*digged*) significantly affected the likelihood of making errors of regularization.

Discussion

In the present study, we investigated whether the distribution of morphophonological patterns in the language, previously shown to impact the inflection of nonwords in unimpaired individuals, impacts production in morphological impairment. To this end, we analysed the past-tense verb production of RMI, an individual with a demonstrated morphological deficit, and found that morphophonological distributions impacted both his accuracy and error patterns in a systematic, measurable way. For regular verbs, it was found that words with inflectional patterns which fit more closely with the overall morphophonological patterns of the language (i.e. words with more phonologically similar words in the lexicon which take the regular past-tense inflection, e.g. *rush*→*rushed*) were less vulnerable to error than those that were more anomalous (e.g. *mind*→*minded*). This suggests that regular verbs, typically regarded as a single, cohesive group within the aphasia literature (e.g. Harris & Humphreys, 2015; Ullman et al., 1997, 2005), are subject to gradient differences in production based on how well they fit the patterns of the language. For irregular verbs, morphophonological pattern distribution was not found to be a significant predictor of accuracy; however, there was a significant impact of morphophonological pattern distribution on RMI's error pattern. We found that the more closely a regularized error (e.g. *dig*→*digged*) fit the morphophonological patterns of the language (i.e. the more phonologically similar words in the language which also take the regular past-tense inflection), the more likely that form was to be produced in error. This finding suggests that in morphological impairment, it is not only factors related to the target word which may impact production, but the structure of the possible errors as well.

Taken together, the results of this study provide evidence that the distribution of morphophonological patterns in the language systematically impacts production in morphological impairment. This finding expands on previous work that found morphophonological patterns in the language impact the way in which unimpaired individuals inflect novel words (Albright & Hayes, 2002; Albright & Hayes, 2003), and suggests that these patterns and their distribution are encoded in a way that also influences the production of known words, impacting morphological processing beyond acquisition. Given that previous work suggests both regular and irregular morphophonological distributions impact production (Albright & Hayes, 2003), the lack of a significant effect on accuracy for irregular verbs was surprising. However, it is important to note that other factors typically predicted to impact production (e.g. frequency and number of phonemes) were also not found to significantly impact accuracy in irregular verbs in this patient. This may indicate that RMI's accuracy in irregular verb production is overall less systematic and predictable than his production of regular verbs, making it difficult to capture potential effects of morphophonological patterns on his production. Future work using a larger, more varied group of patients may be able to provide further insight into this question.

As previous work indicated that morphophonological pattern distribution in the language impacts the inflection of both regular and irregular non-words in unimpaired individuals

(Albright & Hayes, 2003), we predicted that morphophonological patterns would impact the production of both regular and irregular past-tense verbs in this patient. However, because our predictor of interest (confidence score) is highly correlated with regularity, regular and irregular verbs were analysed separately. This allowed us to better examine fine-grained differences *within* these categories which might be otherwise obscured by broader differences between regular and irregular verbs. It also allowed for the analysis of error patterns which only apply to one category (i.e. the regularization of irregular verbs, e.g. *dig*→*digged*). However, analysing regular and irregular verbs separately does not allow for an examination of whether morphophonological pattern distributions impact morphological processing in a gradient way *across* groupings of regularity. While the extremely high correlation of confidence score and regularity did not allow us to explore this possibility (there is no crossover between confidence scores of regular and irregular verbs in our data set, i.e. the confidence score of the most anomalous regular verb is higher than the confidence score of the irregular verb that most closely fits the morphophonological patterns of the language), it is possible that this type of crosscategorical gradation exists in the language.

Historically, the performance of individuals with aphasia on regular and irregular past-tense production has been analysed as a means of determining whether regular and irregular verbs are processed using a single mechanism, or two distinct mechanisms (e.g. Faroqi-Shah, 2007; Harris & Humphreys, 2015; Luzzatti et al., 2001; Miozzo, 2003; Ullman et al., 1997, 2005; Weinrich et al., 1999). We are essentially agnostic on this issue, as adjudicating between these views is beyond the scope of the current work. However, the dual findings of the current study (gradient differences *within* the categories of regular and irregular verbs as well as distinctions in performance *between* these two categories) provide additional data that may be used to constrain both single-mechanism and dualmechanism accounts of morphological processing.

Clinical implications

The current study has several important implications for clinical intervention targeting morphological impairment. First, we present two tasks designed to identify the presence of a morphophonological deficit separable from phonological impairment (Analyses 1 and 2). Verb morphology deficits have been shown to respond to targeted intervention (e.g. Faroqi-Shah, 2013); therefore, identifying the presence of a morphological impairment is essential for determining the most effective intervention strategy and maximizing treatment gains. However, distinguishing whether a patient presents with a morphological impairment can be challenging in clinical practice. Morphological impairment is typically accompanied by a range of other deficits (to our knowledge, there has been no report to date of a patient with a morphological impairment in isolation), and other types of impairment may produce errors which appear similar to morphological errors on the surface, particularly phonological impairment. For many words, the change from stem to inflected form includes an increase in both morphological and phonological complexity (e.g. *walk*→*walked*). Therefore, failure to inflect a word may represent a phonological simplification ([wɔkt]→[wɔk]) or a morphological simplification (*walked*→*walk*). The reading tasks presented in Analyses 1 and 2 of this study, when combined with observation of other language patterns, may

provide an effective way to decouple the effects of morphology and phonology in patients and provide insight into the underlying source of production errors. Further research is needed in order to determine the best use of these tasks and whether the results generalize to a wider population of individuals with aphasia.

The finding that the distribution of morphophonological patterns in the language impacts accuracy and error patterns in past-tense production in an individual with aphasia, may also provide insight into developing effective treatment protocols for morphological impairment.

The fact that morphophonological patterns were found to impact production *within* the categories of regular and irregular verbs is notable in considering treatment for morphological impairment. Much of the literature concerning aphasia and morphology focuses on the regular/irregular distinction of verb inflection (e.g. Faroqi-Shah, 2007; Luzzatti et al., 2001; Miozzo, 2003; Ullman et al., 1997, 2005; Weinrich et al., 1999). Although this distinction is an important area of inquiry with both clinical and theoretical implications, the current data suggest that a more fine-grained approach examining gradient differences within these categories may be necessary to fully understand morphological processing and to formulate the most effective treatment for individuals who present with this type of deficit. Specifically, incorporating a focus on how verbs pattern together in morphophonological groupings may be beneficial. Relatively few formal interventions have been developed for remediation of morphological impairment in aphasia, with more attention given to word-finding and phonological deficits in clinical practice. Of the treatment research that has addressed verb inflection deficits in aphasia (see Faroqi-Shah, 2008 for an overview), none incorporate phonological similarity across verbs and their inflectional patterns. While Faroqi-Shah (2008) did investigate use of a “morphophonological” treatment for verb inflection, it did not include a direct focus on the morphophonological patterns of verb inflection. Rather, the term “morphophonological” was used to denote a focus on oral production of the form in treatment rather than on temporal context (“morphosemantic” treatment).

As the current data suggest that the number of phonologically similar forms which share inflectional patterns influences production, it is possible that phonological structure may be of use within morphological processing intervention. This may involve developing treatment protocols that directly highlight and draw attention to morphophonological patterns in the language. Alternatively, morphophonological patterns may be used in a more indirect manner, for example, as a means to organize treatment targets (i.e. training verbs in groups with similar morphophonological patterns within the context of a given intervention protocol). Similar frameworks have been used in different types of aphasia intervention; for example, contextual priming (in which targets are presented in sets of words which share either semantic or phonological properties) has been used to improve naming performance in anomic patients (e.g. Martin & Laine, 2002; Martin, Fink, Laine, & Ayala, 2004; Renvall, Laine, Laakso, & Martin, 2003). Further systematic investigation is needed to determine to what extent and in what specific ways a similar protocol may be employed in clinical intervention for morphological production.

Conclusions

The current study investigated whether the distribution of morphophonological patterns in the language impacted the past-tense production of RMI, an individual with aphasia. We first presented two analyses that demonstrated that RMI's production is significantly impacted by a morphological impairment that is separable from phonological errors and affects both regular and irregular forms. These were followed by a past-tense elicitation task designed to analyse the impact of morphophonological patterns on RMI's accuracy and error patterns in production. It was found that for regular verbs, words with morphophonological patterns that more closely match the overall patterns of the language were less vulnerable to error than those with more anomalous patterns. Morphophonological pattern distributions were not found to have a significant impact on accuracy in irregular verbs; however, error patterns in irregular verbs (specifically rate of regularization) were significantly predicted by morphophonological patterns in the language.

Taken together, the results of this study extend previous work that has found morphophonological patterns in the language impact non-word inflection, and suggest that the distribution of these patterns also plays a role in spoken production beyond the inflection of novel words. Further research is needed to determine the extent of this role, and to further explore the ways in which it may interact with other lexical factors to impact morphological impairment.

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APPENDIX 1

Stimuli used in Analysis 1 (single-word reading). Words are pairwise matched across morphological complexity to contain the same rime (e.g. *fold-rolled*; subset of homophone pairs [e.g. *rows-rose*] included).

absence	cored	hints
accord	craze	hissed
advise	cries	hoax
amaze	crude	hoes
applause	dance	hold
backs	days	holed
band	daze	hose
banned	dense	implode
bays	dents	insist
beast	dies	jinx
billed	disease	knows
blaze	disguise	lacked

board	ducked	laps
bode	duct	lapse
bold	dude	last
bored	ease	lays
bowed	fade	laze
bowled	fax	leased
brewed	faze	least
brews	fees	links
brood	fence	load
bruise	flowed	locks
build	foes	lord
bussed	ford	lose
bust	fox	lox
cents	frays	lucked
chance	gassed	lynx
chants	gauze	maps
cheese	glaze	mays
clause	glowed	maze
claws	gnaws	minks
clued	grade	minx
coax	graze	missed
code	greyed	mist
cokes	greys	mode
collapse	guild	mowed
conduct	haze	news
cord	hence	node
nose	seize	
packed	sense	
pact	shade	
passed	showed	
past	shows	
patience	sighs	
patients	since	
pause	size	
paws	snows	
pays	soared	
peas	sphinx	
pents	stored	
pheasants	stowed	
phrase	subtract	
pieced	sued	
played	sword	
plays	tacked	

pleas	tact
please	teas
pokes	tease
pose	thinks
poured	those
praise	toad
prayed	towed
prays	tracked
presence	tract
presents	trays
pries	trees
prize	tries
prose	wade
raise	wax
rants	ways
rays	weighed
rents	weighs
rise	whacks
road	whiled
roared	wild
rocks	willed
rose	winks
rowed	wise
rows	
rude	
rued	
ryes	
saws	
sees	

APPENDIX 2

Stimuli used in Analysis 2 (single-word reading). Stimuli included stem and inflected forms of regular verbs (e.g. *sin–sinned*); stem and inflected forms of irregular verbs, pairwise matched to the rimes of the regular stems (e.g. *win–won*); and monomorphemic phonological control words (i.e. two words pairwise matched to the rime of the stem and inflected irregular verbs, but with no morphological relationship to one another [e.g. *tin–ton*])

Regular stem	Regular inflected	Irregular stem	Irregular inflected	Control “stem”	Control “inflected”
free	freed	flee	fled	bee	bed
greet	greeted	meet	met	beet	bet

Regular stem	Regular inflected	Irregular stem	Irregular inflected	Control “stem”	Control “inflected”
side	sided	hide	hid	bide	bid
rig	rigged	dig	dug	big	bug
like	liked	strike	struck	bike	buck
shun	shunned	run	ran	bun	ban
fake	faked	take	took	cake	cook
wing	winged	ring	rang	cling	clang
dry	dried	fly	flew	cry	crew
play	played	slay	slew	day	dew
link	linked	think	thought	ink	ought
smear	smear	tear	tore	fear	fore
pin	pinned	spin	spun	fin	fun
fit	fitted	spit	spat	flit	flat
land	landed	stand	stood	hand	hood
mind	minded	bind	bound	hind	hound
pit	pitted	sit	sat	hit	hat
heat	heated	eat	ate	meat	mate
leak	leaked	speak	spoke	peak	poke
care	cared	bear	bore	pear	pore
reel	reeled	kneel	knelt	peel	pelt
ding	dinged	sing	sang	ping	pang
seal	sealed	steal	stole	real	role
tide	tided	slide	slid	ride	rid
dim	dimmed	swim	swam	rim	ram
remind	reminded	find	found	rind	round
blink	blinked	sink	sank	rink	rank
scoot	scooted	shoot	shot	root	rot
pick	picked	stick	stuck	sick	suck
bake	baked	wake	woke	stake	stoke
sin	sinned	win	won	tin	ton
heed	heeded	feed	fed	weed	wed

APPENDIX 3

Stimuli used in Analysis 3 (past-tense elicitation task). Verb stems were presented in a sentence frame (e.g. Every day I run a mile. Just like every day, yesterday I a mile.) which was presented to the participant both verbally and visually.

Irregular verbs

bear	hang	stride
Begin	hear	strike
bind	hide	strive

bite	hold	swear
bleed	keep	sweep
blow	kneel	swim
break	know	swing
breed	lead	take
bring	leap	teach
buy	leave	tear
catch	light	tell
choose	lose	think
cling	mean	wake
come	meet	weave
creep	mistake	weep
deal	ring	win
dig	run	wind
dive	say	withdraw
do	see	wring
draw	seek	write
dream	sell	
drive	shake	
eat	shoot	
feed	sing	
feel	sink	
fight	sit	
find	slay	
flee	sleep	
fling	slide	
fly	sling	
forget	speak	
freeze	speed	
get	spin	
give	spit	
go	stand	
grind	steal	
grow	stick	

Regular verbs

Arrive
 bake
 balk
 bang
 bask
 blend
 blink
 call

care
chase
chop
claim
clap
cook
cram
cross
dash
dim
dine
drop
dry
fail
fake
flap
flush
free
fret
frown
gain
greet
heat
heave
heed
hop
join
land
lap
leak
like
link
live
look
lop
love
mar
mend
mind
nap
need
owe
pass

pick
pin
pit
plan
play
pray
prowl
pull
push
race
reel
rig
rob
roll
row
rule
rush
sail
scoot
scour
scowl
seal
seem
show
shrug
shun
side
sigh
sin
slam
slap
slip
smear
soar
sort
stalk
stay
stir
stop
tie
toss
try
tug

use
view
walk
weigh
wing

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Table 1.

Error types produced in single-word reading task-varying morphological and phonological complexity (Analysis 1).

Error type (% of errors)	
Morphological (e.g. <i>tracked</i> → <i>tracking</i>)	50% (<i>n</i> = 189)
Phonological (e.g. <i>ford</i> → <i>form</i>)	29% (<i>n</i> = 108)
Semantic (e.g. <i>cord</i> → <i>rope</i>)	2% (<i>n</i> = 8)
Other (e.g. <i>mode</i> → <i>toe</i>)	20% (<i>n</i> = 74)

Note: Percentage of total errors (*n* = 379). Error types were categorized as follows: morphological (deletion, addition, or substitution of an affix); phonological (misproduction with 50% of target phonemes maintained); semantic (related to the target in meaning); and “other” (all errors which did not fall under the previous three categories).

Table 2.

Factors impacting accuracy in single-word reading task-varying morphological and phonological complexity (Analysis 1a).

Fixed effects	All Items			Homophones			Non-homophones (rime-matched)		
	β	z	p	β	z	p	β	z	p
Morphological complexity	-2.563	6.009	< 0.001*	-2.054	4.502	< 0.001*	-3.354	3.913	< 0.001*
Phonological complexity	-0.754	2.083	0.037*	-0.982	2.448	0.014*	-0.530	0.744	0.457
Frequency	0.530	2.747	0.006*	0.501	2.256	0.024*	0.647	1.803	0.071

Note: Dependent variable is accuracy (binary: correct vs. incorrect). Morphological complexity and phonological complexity are binary (monomorphemic vs. bimorphemic and singleton coda vs. coda cluster, respectively).

Table 3.

Overall accuracy (per cent correct) in single-word reading task (Analysis 1a).

		Morphology	
		Simple	Complex
Phonology (coda)	Simple	60% (<i>n</i> = 96) e.g. <i>praise</i>	19% (<i>n</i> = 31) e.g. <i>prays</i>
	Complex	46% (<i>n</i> = 65) e.g. <i>pact</i>	13% (<i>n</i> = 19) e.g. <i>packed</i>

Note: Stimuli orthogonally varied by morphological complexity (monomorphemic vs. bimorphemic) and phonological complexity (singleton coda vs. coda cluster).

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Table 4.

Factors impacting final consonant deletion in single-word reading task-varying morphological and phonological complexity (Analysis 1b).

Fixed effects	All Items			Homophones			Non-homophones (rime-matched)		
	β	z	p	β	z	p	β	z	p
Morphological complexity	-3.209	-5.196	< 0.001*	-1.902	-3.327	0.004*	-5.735	3.657	< 0.001*
Phonological complexity	-1.348	-2.878	0.004*	-0.873	-1.833	0.067	-1.947	1.812	0.070
Frequency	0.660	2.788	0.005*	0.457	1.840	0.066	1.049	1.989	0.047*
Orthographic neighbourhood	0.817	3.344	< 0.001*	0.705	2.782	0.005*	0.813	1.549	0.122

Note: Dependent variable is error type (binary: final consonant deletion vs. other error). Morphological complexity and phonological complexity are binary (monomorphemic vs. bimorphemic and singleton coda vs. coda cluster, respectively).

Table 5.

Final consonant deletion errors for single-word reading task-varying morphological and phonological complexity (Analysis 1b).

		Morphology	
		Simple	Complex
Phonology (coda)	Simple	10% ($n = 6/63$) e.g. <i>praise</i> →[pre]	56% ($n = 72/128$) e.g. <i>prays</i> →[pre]
	Complex	32% ($n = 24/76$) e.g. <i>pact</i> →[pæk]	66% ($n = 80/122$) e.g. <i>packed</i> →[pæk]

Note: Per cent of final consonant deletion errors out of total errors by stimulus type (Analysis 1b). Stimuli orthogonally varied by morphological complexity (monomorphemic vs. bimorphemic) and phonological complexity (singleton coda vs. coda cluster).

Table 6.

Stimuli for single-word reading task including regular and irregular past-tense verbs (Analysis 2).

		Stimulus type		
		Regular verb	Irregular verb	Control
Inflectional status	Stem	<i>sin</i> (<i>n</i> = 32)	<i>win</i> (<i>n</i> = 32)	<i>tin</i> (<i>n</i> = 32)
	Inflected	<i>sinned</i> (<i>n</i> = 32)	<i>won</i> (<i>n</i> = 32)	<i>ton</i> (<i>n</i> = 32)

Note: Six types of stimuli were included: stem and inflected forms of regular verbs; stem and inflected forms of irregular verbs, pairwise matched to the rimes of the regular stems; and monomorphemic phonological control words, (i.e. two words pairwise matched to the rime of the stem and inflected irregular verbs, but with no morphological relationship to one another).

Table 7.

Accuracy (per cent correct) by stimulus type for single-word reading task including regular and irregular past-tense verbs (Analysis 2a).

% correct	Regular verbs (e.g. <i>sin–sinned</i>)	Irregular verbs (e.g. <i>win–won</i>)	Control (e.g. <i>tin–ton</i>)
Stem	71% ($n = 68/96$)	66% ($n = 63/96$)	65% ($n = 62/96$)
Inflected	21% ($n = 20/96$)	41% ($n = 39/96$)	72% ($n = 68/96$)

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Table 8.

Factors impacting accuracy in single-word reading task including regular and irregular past-tense inflections (Analysis 2b).

Fixed effects	β	z	p
Inflection * stimulus type (regular vs. control)	2.432	2.861	0.004*
Inflection * stimulus type (irregular vs. control)	2.262	2.749	0.006*
Inflection * stimulus type (regular vs. irregular)	0.211	0.255	0.799
Frequency	1.407	5.990	<0.001*
Orthographic neighbourhood	0.579	2.858	0.004*

Note: Dependent variable is accuracy (binary: correct vs. incorrect).

Table 9.

Rate of morphological reduction to stem in regular and irregular verbs, and analogous phonological errors (control) in single-word reading task (Analysis 2b).

	Regular verbs (e.g. sinned→sin)	Irregular verbs (e.g. won→win)	Control (e.g. ton→tin)
Inflected→stem errors (% of errors)	50% ($n = 38/76$)	54% ($n = 31/57$)	0% ($n = 0/28$)

Note: Values represent percentage of total errors for each category.

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Table 10.

Error types produced in past-tense elicitation task (Analysis 3).

Error type	Regular verbs	Irregular verbs
Regularization (e.g. dig→digged)	–	49% [<i>n</i> = 124]
Stem maintenance (e.g. dig→dig)	53% [<i>n</i> = 67]	27% [<i>n</i> = 69]
Stem error + -ed (e.g. dig→walked)	15% [<i>n</i> = 19]	4% [<i>n</i> = 10]
Internal vowel change (e.g. dig→dag)	5% [<i>n</i> = 7]	4% [<i>n</i> = 11]
Other morphological inflection (e.g. dig→digging)	4% [<i>n</i> = 6]	2% [<i>n</i> = 4]
Suffixed irregular	–	2% [<i>n</i> = 4]
Other	22% [<i>n</i> = 28]	12% [<i>n</i> = 30]

Note: Values represent percentage of total errors for regular and irregular verbs.

Table 11.

Factors impacting accuracy in regular verb production in past-tense elicitation task (Analysis 3a).

Fixed effects	β	z	p
Confidence score	1.023	3.881	< 0.001*
Number of phonemes	-0.814	-3.378	< 0.001*
Phonological neighbourhood	0.297	1.379	0.168

Note: Dependent variable is accuracy (binary: correct vs. incorrect).

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Table 12.

Results of mixed-effects, logistic regression model analysing accuracy in irregular verb production in past-tense elicitation task (Analysis 3b).

Fixed effects	β	z	p
Phonological neighbourhood	0.691	2.112	0.035*
Number of phonemes	-0.635	-1.933	0.053

Note: Dependent variable: accuracy (binary: correct vs. incorrect).

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