Laboratory Phonology
Journal of the Association for Laboratory Phonology

Bundgaard-Nielsen, R. L., Baker, B. J., & Wang, Y. (2026). Complex morphology, complex processing: Phonological hardening and *ŋu*-insertion in Wubuy. *Laboratory Phonology: Journal of the Association for Laboratory Phonology*, 17(1), pp. 1–38. DOI: https://doi.org/10.16995/labphon.28014

Open Library of Humanities

Complex morphology, complex processing: Phonological hardening and *ŋu*-insertion in Wubuy

Rikke L. Bundgaard-Nielsen*, School of Languages & Linguistics, University of Melbourne, Australia; The MARCS Institute for Brain, Behaviour and Development, Australia, rikkieb@unimelb.edu.au

Brett J. Baker, School of Languages & Linguistics, University of Melbourne, Australia, bjbaker@unimelb.edu.au

Yizhou Wang, School of Languages & Linguistics, University of Melbourne, Australia, yizwang3@unimelb.edu.au

*Corresponding author.

This paper investigates how speakers of Wubuy (Nunggubuyu) process two linked morphophonological alternations—*phonological hardening* and ŋu-*insertion*—using two Two-Alternative Forced Choice experiments. Wubuy is highly polysynthetic; many stems alternate between root-initial continuants and place-matched stops (e.g., *-waɭaŋi* versus *-paɭaŋi* 'to paint') or require the meaningless syllable /*ŋu*/ before underlying stop-initial morphemes. Experiment 1 tested over- and under-application of continuant-stop alternations with and without a 500 ms pause, which is introduced to increase processing time; Experiment 2 probed preferences for *ŋu*-insertion across faithful stops, hardened forms, continuants and single-feature mispronunciations. Results show listeners prefer grammatical outputs but display asymmetric acceptance: processing of hardened verbs incurs processing cost and benefits from extra pause, while vowel-initial verbs behave as if dual-listed and are unaffected by pause. For *ŋu*-insertion, speakers strongly prefer grammatically required /*ŋu*/, tolerate single-feature mispronunciations to varying degrees, and show gradient rather than categorical judgements. Overall findings favor a model in which canonical forms are stored and context-sensitive phonological rules are applied during processing, with selective contributions from listing for some alternations. The experiments provide typologically rare results from an Australian language and argue for integrated dual-route accounts. The research limitations include small participant numbers and culturally constrained data collection.

Laboratory Phonology: Journal of the Association for Laboratory Phonology is a peer-reviewed open access journal published by the Open Library of Humanities. © 2026 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See http://creativecommons.org/licenses/by/4.0/. Articles published by the Open Library of Humanities may also contain other CC-licensed material, or material used or reproduced under an exception or limitation to copyright. Such material is not subject to the article's license. It is either marked with its own license, or marked that it has been reproduced with permission or under fair-use.
OPEN ACCESS

1. Introduction

The relationship between morphological complexity and lexical access has been a paramount question in the field of psycholinguistics for decades, with an increase in research on morphological processing since the 1970s. However, the vast bulk of research in this domain has been carried out on a handful of languages (e.g., English, Dutch, German) with very similar morphological characteristics: roots frequently of just one or two syllables, few if any inflectional prefixes, and the bulk of morphology being suffixal (Anand et al., 2011; Blasi et al., 2022; Bornkessel-Schlesewsky & Schlesewsky, 2016; Collart, 2024; Kidd & Garcia, 2022; Norcliffe et al., 2015). Similarly, more than half of all morphological processing research has been conducted on suffixation (Cayado & Rastle, 2025).

The present research departs from this approach and examines the processing of two morphophonological patterns of alternation in the Australian Indigenous language Wubuy. Wubuy, also known as Nunggubuyu (Heath, 1984; ISO 639-3 code *nuy*), is a highly polysynthetic language in which word-internal morphological boundaries exhibit two unusual, linked patterns of morphophonological alternation: *phonological hardening* and ŋu-*insertion*, both involving the initial segments of stems. Phonological hardening (Section 1.1) results in morpheme-initial phoneme alternations between continuants and stops under conditions where the preceding morpheme ends in a non-continuant (a nasal or a stop; there are no fricatives in the inventory), as in Example (1) and Example (2), where the verb *wulṯa* 'cut' has an initial segment /w/ following continuants as in (1), but is realised as *kulṯa* following non-continuants such as the stop /c/ in (2).

(1) [ŋa-wu-**w**ulṯa + ŋi]
1sg-NEUT-cut + PAST.CONT
'I was cutting it (NEUT)'

(2) [ŋa-wu-ɻuluc-**k**ulṯa + ŋi]
1sg-NEUT-bough.shade-cut + PAST.CONT
'I was cutting a bough shade (NEUT)'

The process of *ŋu*-insertion (Section 1.1) involves the appearance of the meaningless string */ŋu/* 'Ø' before (underlyingly) stop-initial stems under conditions which are partly phonological and partly morphological, but which partially overlap with the conditions for hardening, so that all environments that condition hardening can also condition *ŋu*-insertion. "Hardened" verbs like *kulṯa,* in Example (2), contrast with underlyingly stop-initial inflected verbs such as *kucukucaani* 'tickle.PAST.CONT', in Example (3), where it follows a vowel-final agreement prefix. Verbs which are underlyingly stop-initial require a preceding /ŋu/ where they follow a bound stem, as in Example (4), where the verb follows an incorporated noun. The approximately 1% of agreement

prefixes that don't end in a vowel also condition insertion of /ŋu/, along with any other non-agreement morphology that precedes the verb, regardless of the final segment.

(3) /ŋani-**k**ucukucaani/
3masc/1sg-head-**Ø**-tickle. PAST.CONT
'He tickled me'

(4) /ŋani-jina**k**-*ŋu*-**k**ucukucaani/
3masc/1sg-head-**Ø**-tickle.PAST.CONT
'He tickled me on the head'

Morphophonological phenomena such as initial hardening and *ŋu*-insertion are typologically rare in the world's languages but serve as excellent phenomena through which to study the processing of complex morphophonology. Indeed, such phenomena pose a challenge to models of processing because assumptions of input fidelity—i.e., that the input matches and therefore activates forms in the lexicon—cannot necessarily be satisfied. This is especially the case for changes to the initial segments, which have been demonstrated to be particularly important to lexical access (Cutler, 2008; Cutler et al., 1985).

The central questions of our research are: How do speakers process the related phenomena of phonological hardening and *ŋu*-insertion, and what theories of morphology—and the processing of morphology—can best account for the behavior of speakers? Fundamental to this pursuit is the question of whether complex words are stored as wholes in speakers' mental lexicons or stored in partially or completely analysed forms (i.e., as morphemes or morpheme combinations) with some degree of computation involved in both comprehension and production (Amenta & Crepaldi, 2012; Marslen-Wilson, 2007; Zwitserlood, 2018). Or, can we allow for both storage and computation to varying degrees, as in *dual-route models* (Frauenfelder & Schreuder, 1991; Ullman et al., 1997; Ullman, 2001, 2004) based on factors such as productivity or regularity?

The predictions of these theoretical approaches differ, and studies like the one presented here may contribute to the assessment of their explanatory and predictive power. In full-listing approaches, only words have lexical entries (not sub-lexical morphemes), and so every complex word must be accessed by finding a matching entry in the mental lexicon (Baayen et al., 2011; Gonnerman et al., 2007; Plaut, 2011; Rueckl et al., 1997; Rumelhart & McClelland, 1986; Westermann & Ruh, 2012). These models typically assume an associative-connectionist network to model lexical access and retrieval. It is unclear how such approaches would deal with deviations from grammatical output such as mispronunciations or failures to implement a phonological rule, unless there is a separate mechanism to license such deviations from the canonical (underlying) form. As we have argued elsewhere (Bundgaard-Nielsen et al, 2025, p. 4):

> Few would argue with the fact that [kʰæt] 'cat' is stored in the minds of English-speakers as /kæt/ and will not necessarily be well-recognised if produced as [gæt] (a change in the voicing specifications of the initial segment that crosses the phonetic VOT boundary) or [pæt] (a change in place of articulation), or [ɣæt] or [ɯæt] (a change in manner of articulation from a stop to a fricative [ɣ] or approximant [ɯ] at the velar place of articulation) by speakers. Changes of this sort potentially lead to activation of the wrong set of lexical competitors where the phonetic realisation results in a phonological substitution (/kæt/ 'cat' to /pæt/ 'pat' or /gæt/ 'gat', or no activation at all). These 'wrong paths' would require reinterpretation or repair of the input at some later point.

This is something that poses a significant challenge to models of processing, including associative and full listing models, that adopt a strictly linear approach.

In contrast, at least in some full-parsing and dual-route approaches (Chialant & Caramazza, 1995; Clahsen, 1999; Marslen-Wilson & Warren, 1994; Pinker & Ullman 2002; Schreuder & Baayen 1995; Taft, 2004; Ullman, 2001, 2004; Ullman et al., 1997), words are retrieved by parsing out morphemes and accessing lexical entries associated with those morphemes, including complex words containing them, at least in the case of productive/regularly formed words. Under these views, deviations from canonical forms can either be reverse engineered to reveal an existing underlying form—*incurring a processing cost*—or, in the case of dual-route models, result in direct activation of parallel listed forms in the lexicon. Mispronunciations that cannot be reverse engineered—such as the */pæt/ 'pat' or /gæt/ 'gat'/* example from Bundgaard-Nielsen et al. (2025)—will either be repaired or rejected as unrecoverable (nonsense). See Blanco-Elorrieta et al., (2021) for discussion and evidence that repair of mispronunciation requires top-down processing. It is precisely these kinds of outputs that are examined here.

To address these questions, we examine speakers' tolerance for deviations in the implementation of phonological hardening and *ŋu*-insertion, and how context affects their judgements. We do so in two Two Alternate Forced Choice (2AFC) experiments testing native speaker processing of Wubuy phonological hardening and *ŋu*-insertion. We show that Wubuy listeners do not simply accept all and only the grammatical outputs, and reject all the ungrammatical ones, which we might expect based on full listing models. Rather, they have variable rates of acceptance even of fully grammatical forms depending on the kind of grammatical processes and violations involved. The data also suggests that some forms are more costly or difficult to parse, suggestive of a computational process, in a manner inconsistent with full listing.

Our explanation for this behavior relies on the proposal that speakers store not all surface forms of morphemes in particular contexts (as in the full listing approach) but rather store "canonical" or "underlying" forms, from which all surface forms can be derived by the application of general processes, as proposed in the generative model of phonology in Chomsky and Halle (1968)

and many works since (e.g., Lahiri & Marslen-Wilson, 1991; Gaskell & Marslen-Wilson, 1996; 1998; Gow, 2001; 2002, for similar approaches). The results reported here have implications for models of the lexicons of polysynthetic languages, as well as for the evaluation of theories of phonology, morphology, and language processing.

1.1. Morphophonological alternation in Wubuy

Wubuy (Heath, 1984) is a Non-Pama-Nyungan language spoken in a remote region of eastern Arnhem Land in the Northern Territory of Australia. It is related to other languages of Arnhem Land with larger speaker populations, such as Anindilyakwa (Van Egmond, 2012) and Bininj Gun-wok (Evans, 2003), and others that are effectively moribund, such as Dalabon (Evans, Fletcher, & Ross, 2008), Ngandi (Heath, 1978), and Ngalakgan (Baker, 2008; Merlan, 1983).

We estimate that Wubuy is spoken by around 60 fluent first language (L1) speakers primarily in the remote settlement of Numbulwar on the Gulf of Carpentaria (Bohn & Bundgaard-Nielsen, 2021). It is likely also an L2/L3 for some speakers in adjacent communities in north-east Arnhem Land, but the precise number of speakers is difficult to assess. Wubuy is primarily spoken by older people; children and young people in Numbulwar speak Kriol (an English-lexified creole: see Sandefur, 1982; Bundgaard-Nielsen & Baker, 2016), although they are often addressed in Wubuy by older members of the community and appear to have (some) receptive language skills.

Wubuy has a typical Australian phonological inventory (see **Table 1**), with four contrastive coronal places of articulation in stops and nasals, plus a dorso-velar and bilabial series. All four coronal series contrast word-initially as well as medially (which is also highly unusual, cross-linguistically, in Australia: Baker & Harvey, 2026, p. 74). Wubuy lacks voicing or constriction contrasts in obstruents; the obstruents are represented with the voiceless IPA series here, although their phonetic voicing and constriction values vary.

	Labial	**Lamino-dental**	**Apico-alveolar**	**Apico-retroflex**	**Lamino-alveopalatal**	**Dorso-velar**
Stop	p	t̪	t	ʈ	c	k
Nasal	m	n̪	n	ɳ	ɲ	ŋ
Lateral		l̪	l	ɭ		
Trill/tap			r			
Approximant	w			ɻ	j	

Table 1: Consonant inventory of Wubuy (after Heath, 1984).

Wubuy is characterised by extensive morphophonological alternations. Due to a historical process of chain shift lenition (Heath 1978; 1984), Wubuy morphemes overwhelmingly

begin in continuants, including vowels. A subset of the phonemic continuants {w, j, ɻ, r, l̪} alternate in a predictable fashion with place-matched stops following non-continuants (nasals and stops) in a process dubbed hardening in Heath (1984); see Example (1) and Example (2), where the verb-initial continuant /w/ alternates with /k/ when a nasal or stop precedes (other w-initial morphemes alternate with /p/: the difference is lexically specified and unpredictable). Phonological hardening is not a minor phenomenon in Wubuy: ~57% of all roots in the lexicon of Heath (1982) begin in one of these five alternating continuants (Bundgaard-Nielsen & Baker, 2014), more than half of them in /w/. Phonological hardening is completely productive and exceptionless in Wubuy: All morphemes, including verbs, which begin in {w, j, ɻ, r, l̪}, undergo this hardening in the relevant inter-morphemic environment.[1]

Phonological hardening operates in parallel with a second process—*ŋu*-insertion—in which the meaningless string */ŋu/* is inserted before underlyingly (i.e., not derived from a continuant by hardening) stop-initial morphemes, when they occur in environments which partially overlap the environment for hardening, as in Example (4), presented above. Here, underlying stop-initial verbs such as *kucukucaani* 'tickle.PAST.CONT' must have a preceding string *ŋu* if either of the following conditions is met:

(a) the preceding morpheme is one of the only three agreement prefixes ending in a non-continuant (out of the approximately 350 agreement prefix forms), or

(b) the preceding morpheme is a lexical stem of any phonological shape.

In Example (4), the final stop of the preceding morpheme *jinak* 'head' is (optionally but frequently) deleted in production, but we infer its presence because of the behavior of verbs that begin in continuants: these occur in their hardened, stop-initial forms following *jinak* and similar incorporable nouns ending in stops, regardless of stop realization. Heath (1984; and compare Nyhuis, 2023) argues that *ŋu*-insertion thus serves as an indication that the following morpheme is underlyingly stop-initial, because without it, a phonetic morpheme-initial stop could be underlying or derived, following a non-continuant in the previous morpheme, as in (4). Accounting for the parsing of this semantically empty element is difficult within any linear framework, including associative or listing models of processing, as the need to insert */ŋu-/* only arises once the lexical specifications—or at a minimum, the onset—of the following morpheme can be known, requiring a degree of "look-ahead" commonly ruled out in morphological theories (e.g., Simpson & Withgott, 1986, p. 155; Carstairs-McCarthy, 1987).[2]

[1] We use IPA representations throughout, rather than orthography. None of the Australian languages exemplified herein has a voicing contrast in stops, and phonetic voicing varies, regardless of the transcription practice implemented for each language.

[2] Although morphological models such as Lexical Morphology and Phonology (Kiparsky 1982, 2000) as well as a-morphous models (e.g. Stump 2001) would ordinarily assume that words are built from the root outwards, presum-

1.2 Competing theories of word formation

Morphophonological patterns such as Wubuy phonological hardening and *ŋu*-insertion challenge several models of word-formation. Under associative models of morphology like Construction Morphology (e.g., Booij, 2018; Nyhuis, 2023) and Relational Morphology (Jackendoff & Audring, 2020)—as well as under linear and associative models of word recognition (e.g., the Cohort Model: Marslen-Wilson & Welsh, 1978; TRACE: McClelland & Elman, 1986; Shortlist B: Norris & McQueen, 2008)—language acquisition is "item based." This means that "the composition of a word or sentence involves clipping together stored pieces [words or morphemes, depending on the model] in such a way that every element of the composed structure is accounted for in terms of one stored piece or another" (Jackendoff & Audring, 2020, p. 4; our insertion in brackets). Lexico-grammatical choices are thus explained primarily by complex patterns of parallel associations between (adjacent) elements. These elements form independent systems, connected by linkages that create "correspondences between components rather than derivations from one component to another" (Jackendoff & Audring, 2020, p. 2).

Under associative and similar full-listing models, phonologically conditioned changes or alternations such as those in Wubuy must be accounted for as non-derivational and parallel, and the involved morphemes/words must be selected in a one-step process from multiple equivalent forms in the lexicon, based on their co-occurrence patterns in the input. While frequency in the input might affect the strength of the linkages between co-occurring elements, such that *infrequent* sequences are less accurate or even slower, for *frequently* occurring sequences, these models would expect speakers/hearers to select the appropriate grammatical sequence of morphemes with ease and high levels of accuracy. This is what we would expect in Wubuy, given that both hardening and *ŋu*-insertion are highly frequent and obligatory (see Section 1.1). Note that despite talking of *words* here, Wubuy verbs are complete propositions, translating into entire sentences in English as per the first four examples, and their processing shares aspects of the processing of sentences in some respects. They can also have the prosodic structure typical of phrases, including internal major junctures characteristic of Intonational Phrase boundaries (for a discussion, see Bundgaard-Nielsen & Baker, 2020).

Under competing rule-based analyses, building on Chomsky and Halle (1968), individual morphemes have one canonical phonological shape in the lexicon, which must be selected prior to the environment triggering the application of any (morpho-)phonological rules (Levelt, 1989; Levelt et al., 1999). This is a sequential process (even if constraints on surface forms are computed in parallel, as in Optimality Theory: Prince & Smolensky, 1993), and the identification

ably starting with the verb in examples like (4). In that case, the speaker/producer would need to know either (a) the morphological type of the 'next' morpheme (e.g., incorporated noun as in [4] vs. agreement prefix as in [3]) in order to decide whether to insert */ŋu-/*), or else (b) know that the upcoming (i.e., preceding) agreement prefix was one that ended in /n/. Either way then, *ŋu*-insertion requires a kind of look-ahead; see Nyhuis (2023, p. 103).

and implementation of necessary phonologically conditioned changes presumably increase the processing demands of spoken word recognition and comprehension when a phonologically conditioned change must be applied. We are aware of no work on this specific issue, but see Bentum et al. (2019), Gaskell & Marslen-Wilson (1996; 1998) and, more recently, Stockall & Gwilliams (2023). A rich literature has examined the processing (recognition) of words produced in canonical—correct, clear, unreduced—phonetic form relative to phonetically reduced or mispronounced forms. Such research generally shows better recognition for canonical forms, though non-canonical word recognition improves when contextual cues are strong (see e.g., Brouwer et al., 2013) and when non-canonical forms are highly frequent (see e.g., Bürki et al., 2018).

In the case of the Wubuy hardening phenomenon, we would expect application of a hardening rule to induce greater processing cost than non-application of a rule (no change, as the trigger for change is absent) and likely higher error rates and greater time cost associated with rule application. Such asymmetrical performance is at odds with the predictions from full listing models, especially if stark differences in the frequency of forms are not apparent. Other models offer more flexible processing paths. The Dual-Route Hypothesis (Frauenfelder & Schreuder, 1991; Ullman et al., 1997; Ullman, 2001, 2004) suggests that regular (predictable) and irregular (unpredictable) patterns might be processed in two different ways. While rule-governed regular patterns are processed implicitly, irregular patterns are retrieved from declarative memory.

Since most of the processing literature has focused on a very narrow typological range of languages, there is limited literature on similar or related types of processes affecting the initial segments of morphemes. Initial consonant mutation in Celtic languages, such as Welsh and Gaelic, and word-initial mutation and lenition in the Australian language Mawng, are two of the rare counterexamples. In Celtic languages such as Welsh, the initial consonants of nouns alternate depending on their grammatical environment, e.g., the word /pont/ ‘bridge’ may appear also as /bont/ or /font/ (Ball & Müller, 1992; Fife & King, 1998). But Celtic mutations cannot be predicted based on the synchronic phonology (i.e., in terms of the local segments in the environment). Rather, the conditioning is dependent on syntactic factors like ‘definite NP’ or ‘genitive NP’. Hence, processing accounts of Celtic mutation rely on accessing items in memory (Ussishkin et al., 2017).

Mawng is also described as having lexicalised initial mutations in verb and noun roots (Evans, 2000, p. 102), as shown in Example (5) in bold. These mutations could presumably be accounted for in a similar way to Welsh mutations. Mawng, however, is also described as having *synchronic* lenition processes affecting initial segments at word boundaries (Capell & Hinch, 1970, p. 44), as exemplified in Example (6). Example (6)a and Example (6)c show that initial /g/ can vary between stop and approximant realisations, following a vowel in the preceding

word. This variation is not licenced/observed following a non-continuant, as in Example (6)b and Example (6)d.

(5) a. a-**m**awur ‘their arms’
3PL-arm

b. **b**awur ‘his arm’
3.arm

(6) a. ge [**g** ~ **ɣ**]apala
it.goes boat
‘the boat goes’

b. gaɾgbin [**g**]apala /*ɣabala
big boat
‘big boat’

c. mada [**g** ~ **w**]ubuɲ
VEG.the canoe
‘the canoe’

d. marig [**g**]ubuɲ/*wubuɲ
NEG canoe
‘not a canoe’

In contrast with Celtic languages, the processing of lenited onsets in Mawng invokes accounts based in the phonetics/phonology/lexicon interface (Bundgaard-Nielsen et al., 2025) and has been argued to be context-conditioned (Capell & Hinch, 1970; Shaw et al., 2020). Together, this suggests that different languages may rely on different processing strategies: some patterns may best be accounted for by associative patterns, while others are best accounted for through rule application. Other languages may require speakers to use both approaches and handle some patterns via associative patterns and expansive listing and others via rule application, as suggested, for instance, by the Dual-Route Hypothesis (Chialant & Caramazza, 1995; Clahsen, 1999; Marslen-Wilson & Warren, 1994; Pinker & Ullman 2002; Schreuder & Baayen 1995; Taft, 2004; Ullman et al., 1997; Ullman, 2001, 2004), and applied by Baker (2008) in an analysis of the Australian language Ngalakgan.

1.3 The present studies

In what follows, we test the effect of phonological hardening and *ŋu*-insertion on word processing in two Two-Alternate Forced Choice (2AFC) experiments with speakers of Wubuy. Experiment 1 (Section 2) tests the effect of over- and under-application of phonological hardening on word recognition in a two-part experiment which differs only in whether a short 500 ms pause has been

inserted before the hardened target verb root. This pause provides participants with additional time to process the frame and thus identify the need for hardening. Since hardening is such a frequent process in Wubuy (see Section 1), we assume that speakers accord it a significant degree of attention. The results indicate that Wubuy speakers find it easier to select the target form of a verb if it does not require hardening, and accuracy is enhanced when a pause is artificially inserted before the target verb to allow parsing of the conditioning context. The existence of a mid-word pause does not cause a naturalness problem: word-internal pauses occur frequently in unmonitored speech in Wubuy and are accepted—indeed, even preferred in some cases—by speakers in a previous 2AFC experiment (Bundgaard-Nielsen & Baker, 2020), even where a pause separates the environment for hardening from its target as in /ŋa-Ø-ɻaŋa- ... kult̪aŋi/ (1sg-RESID-branch-cut.PAST.CONT), where '...' indicates inserted pause and kult̪aŋi is the same hardened verb as in (2), hardened because of preceding noun /ɻaŋak/ 'branch' where the final /k/ has been deleted in the produced form. The results are largely consistent with generative/rule-governed models, though the processing of some lexemes might rely on listing or memory-based approaches (see Section 2.2.1).

Experiment 2a (Section 3.2) tests *ŋu*-insertion preference with verb forms that vary in their initial segment characteristics—stop-initial, continuant-initial, hardened and stop mispronounced as continuant. Experiment 2b (Section 3.3) tests verb form preference in frames with or without *ŋu*-insertion. The results indicate that Wubuy speakers prefer grammatical utterances in both experiments and that grammatical errors and mispronunciations disrupt processing in gradient ways that are, again, not straightforwardly compatible with linear accounts of word recognition, such as full listing models.

Together, the studies suggest that language phenomena like the ones examined here—requiring speakers/listeners to process sequences of morphemes that change shape in ways that are not forwardly predictable—incur a processing cost that is hard to explain in approaches relying on linear and probabilistic associations or connections (Zwitserlood, 2018). Rule-based accounts may have more success accounting for such patterns, and the results presented here do indicate that correct parsing of this kind of language material is *costly* for the listener in ways consistent with rule-based assumptions.

However, before we provide the details of Experiment 1 and Experiment 2, we wish to preface these sections with additional background. In many Indigenous Australian communities, death taboos are observed that prevent individuals from naming, looking at images, photos and videos of, and/or listening to recordings of other Indigenous people who have passed away, particularly people who are well-known to them, e.g., close family or other community members. This is relevant here, because, very sadly, the speaker who produced the stimulus materials for Experiment 1 and Experiment 2 passed away during the data collection phase

(data was collected during several field trips). Consequently, we are unable to collect further data using these materials for cultural reasons. The studies were approved by a Human Ethics Panel at the University of Melbourne (#26884) and funded by the Australian Research Council (DP180100821).

2. Experiment 1: Phonological hardening

2.1 Method

2.1.1 Participants

Fourteen speakers of Wubuy participated in the experiment. The participants (11 women) ranged in age from approximately 40 to 70 years. All participants were fully fluent native speakers of Wubuy and a resident in Numbulwar at the time of testing. The participants were recruited by word of mouth in the community of Numbulwar. The participants constitute approximately 25% of the speaking population (see discussion in Bohn & Bundgaard-Nielsen, 2021). This population is predominantly older, as the community has been undergoing language-shift to the English-lexified contact variety Kriol since the early 1970s (Sandefur, 1982; Bundgaard-Nielsen & Baker, 2016).

Data from four participants was subsequently excluded from the analyses in Section 2.2, leaving the data from ten participants for analysis. One participant failed to complete the experiment, and three participants had difficulty with understanding or remembering task instructions and performed at chance level. All data from the remaining 10 participants was retained and included in our analyses. This rate of participant success is not uncommon in the community where this research was undertaken, as familiarity with experimental research, information technology competence and literacy can be very limited. It is also possible that these participants had undiagnosed hearing loss (hearing loss is common in Indigenous communities in Australia), and their difficulties with the task arose from, or were compounded by, hearing impairment. We did not screen participants for hearing loss, and it is possible that participant self-reporting of hearing loss in the pre-experiment language background questionnaire was not reliable.

2.1.2 Materials

The experimental materials consisted of a 2AFC experiment in two parts (Experiment 1a; Experiment 1b). In each part of the experiment, participants were presented with pairs of one of four complex Wubuy words and were asked to indicate which of the pair they preferred. The four complex words consisted of the prefix *nuŋaa-* (you/her + BENEFACTIVE), followed by one of four incorporated nouns (*ṭarpic* ‘thigh’; *ʈaŋak* ‘branch’; *paɳca* ‘arm’; *ṭukanta* ‘leg’), and then by one of four verb roots, either in a canonical (continuant-initial) or a hardened (stop-initial) form: *-l̪iɲ* ‘to chop (Past Punctual)’ vs. *-ṭiɲ*; *-waɭaŋi* ‘to paint (Past Continuous)’ vs. *-paɭaŋi*; *-waɭpumana* also ‘to paint (Present)’ vs. *-paɭpumana*, as well as a pair of verb alternants that differ in terms of the

presence vs. absence of initial /k/, another common pattern in the Wubuy lexicon: *-aajuu* 'to cut (Past Continuous)' vs. *-kaajuu*; (see **Table 2**). Two of the four incorporated nouns (*ṯarpic* 'thigh'; *ʈaŋak* 'branch') are stop-final and induce hardening of the initial segment of the following verb stem, while the other two (*paɳca* 'arm'; *ṯukanta* 'leg') do not.[3]

Prefix	Incorporated noun	Verb root
nuŋaa- *'you/her.BEN'*	paɳca *'arm'*	-l̪iɲ, -ṯiɲ *'chop.PAST.PUNC'*
	ṯukanta *'leg'*	-aajuu, -kaajuu *'cut.PAST.CONT'*
	ṯarpic *'thigh'*	-waɭaŋi, -paɭaŋi *'paint. PAST.CONT'*
	ʈaŋak *'branch'*	-waɭpumana, -paɭpumana *'paint.PRES'*

Table 2: Wubuy target words.

The four target verb roots were selected for this experiment in collaboration with a Wubuy-speaking consultant with many years of involvement with Wubuy language documentation, research and teaching, to ensure that the verbs and nouns chosen would be well-known by all speakers of Wubuy and the semantic content would be socially and culturally meaningful and readily imaginable. The target verb *-aajuu* 'to cut', however, differs from the other three verbs *-l̪iɲ* 'to chop', *-waɭaŋi* 'to paint', and *-waɭpumana* also 'to paint', in that it is vowel—not consonant—initial, and we therefore treat this verb separately in our analysis, as the process that results in the form *-kaajuu* can be argued to be a form of *stop insertion*, rather than phonological hardening of an underlying continuant to a stop with the same Place of Articulation (POA).

The complex agreement plus Benefactive prefix, represented underlyingly as *nuŋaaK-* in Heath (1984; the 'K' represents an abstract archiphoneme that conditions hardening), always surfaces as *nuŋaa-* with no /k/ but with hardening of any underlying continuant consonants which follow (as well as insertion of /k/ for vowel-initial verbs) due to the opaque phonological interaction described in Section 1 (see Nyhuis, 2023, p. 271 for discussion of the variable implementation of k-deletion in Wubuy). All the incorporated nouns in our stimulus list are thus also phonologically-derived forms with hardened initial consonants. The constrained stimulus

[3] Heath (1984) claims that deletion of /k/ before other consonants is exceptionless in Wubuy, and so incorporated nouns like *ɻaŋak ~ ʈaŋak* are commonly produced as *ɻaŋa ~ ʈaŋa*. But recent work by the current authors and Nyhuis (2023) demonstrates that velar stop deletion is, in fact, a variably implemented rule for current speakers of Wubuy. Current speakers of Wubuy accept and produce forms such as *nuŋaa-ʈaŋak-ṯiɲ* (without /k/ deletion), which form part of the stimulus materials.

set (just four verbs) reflects the need to control the complexity and duration of the experiments to suit the characteristics of the Wubuy research participants, who have very low familiarity with research paradigms and information technology. This potentially has consequences for generalizing the study.

The same female Wubuy speaker who consulted on the stimulus development also produced the complex word stimuli. The stimuli were recorded in a quiet home in Numbulwar using a PMD660 Marantz flash-RAM digital recorder with a DPA d:fine headset microphone, with a 16-bit sampling depth at a sampling rate of 44.1 kHz. During the recording session, the speaker was asked to produce the prefix *nuŋaa-* followed by each of the four nouns, followed by a pause, in which she *imagined* producing a verb stem. This approach ensured that the intonation contour for the incorporated noun did not bear unusual phrase-final intonation. We adapted the inverse approach to the elicitation of the verb stems: The speaker was asked to imagine producing *nuŋaa-* prior to the target verb stem, ensuring that the intonation contour of the verb stem was not listing intonation. This ensured that each half of the cross-spliced stimuli were intonationally matched but did not contain coarticulary information about the preceding or following segments. The speaker produced several utterances of each *nuŋaa-+NOUN* frame, and the selection of each element was based on clarity, pitch, and naturalness in the final frame matchup.

The four *nuŋaa-+NOUN* frames were individually normalized and cross-spliced with individually normalized elicitations of the four non-hardened and four hardened verb stems by the same speaker with phrase final intonation in *Praat* (Boersma & Weenink, 2014). This procedure created a total of 16 word-pairs. In eight of the 16 pairs, one word exhibited expected hardening, and the other word exhibited over-application of hardening. In the other eight pairs, one word exhibited expected hardening, and the other word exhibited underapplication of hardening. Each pair was presented twice (order counterbalanced), producing 32 pseudo-randomized trials (see **Table 3**). Experiment 1b differed from Experiment 1a only in that a 500 ms period of silence was inserted before the target verb in each of the words to manipulate the amount of processing time available to participants.

Condition	Underlying form	Paired stimuli
No hardening	nuŋaak-waɳ**c**a-l̪iŋ	☞ [nuŋaapaɳcal̪iŋ] (canonical) 💣 [nuŋaapaɳcaṯiŋ] (hardening over-applied)
Hardening	nuŋaak-l̪arpi**c**-l̪iŋ	💣 [nuŋaaṯarpicl̪iŋ] (canonical: hardening under-applied) ☞ [nuŋaaṯarpicṯiŋ] (hardened)

Table 3: Sample experiment conditions (☞ = expected response, 💣 = incorrect response). Each condition was presented with or without a 500 ms pause inserted before the target. "Canonical" here means "underlying, not derived."

2.1.3 Procedure

Participants completed Experiment 1a and Experiment 1b in a single session in a quiet home in Numbulwar or Darwin, in the presence of the first and second authors and a Wubuy speaker well-known to the participants. All testing instructions were provided in English by the first and second authors who do not speak Wubuy sufficiently fluently to give adequate instructions in Wubuy. The Wubuy speaker who produced the stimuli also provided instructions in Wubuy, and answered or asked questions in Wubuy when necessary or requested by the participants. Prior to the experiments proper, all participants took part in role-playing the experiment. During the role play, each participant chose between correct and incorrect utterances produced by the Wubuy speaker or the second author, with reference to the experimental screen display. The practice sentence pairs were of a different type to those included in the experiment, and the role-playing practice sessions continued as long as the participants wished, ensuring confidence with the paradigm (without exposure to the experimental materials).

The presentation order of Experiment 1a and Experiement 1b was counter-balanced so that seven participants completed Experiment 1a (i.e., No Pause) first, while seven participants completed Experiment 1b (i.e., Pause inserted) first. The participants were presented with the word pairs through headphones attached to a MacBook computer. It displayed two line drawings of faces, which indicated to the participants that they would hear two speakers. The participants were directed to imagine that the two speakers were each trying to say the same thing.

The participants were instructed to indicate which of the utterances they preferred (the first or the second), and they could do so either by pointing to the first or second line-drawn face on the screen, saying “number one” or “number two” (in either English or Wubuy, as they preferred), or raising one or two fingers to indicate their preference. This approach deviates from the approach typically taken but accommodates to the test-taking profiles and preferences of the participants, many of whom are unwilling or reluctant to use information technology like laptop computers, have low literacy and, in some cases, find requests to give the standard key stroke response intimidating. This and similar approaches have been successfully implemented in previous experimental work on Wubuy (Bundgaard-Nielsen & Baker, 2020) and other Indigenous Australian languages (Bundgaard-Nielsen et al., 2025). The participants were free to listen to each word pair as many times as they liked before recording their response. All participants were given an open-ended rest break between the two parts of the experiment.

2.1.4 Predictions

As outlined in the introduction, phonological hardening in Wubuy must be accounted for as non-derivational and parallel under parallel-associative and similar full-listing models (as it is in Nyhuis, 2023), and the correct forms must be selected from the available forms in the lexicon to ensure that they match the distribution in the input. This entails that we would predict the same

level of accuracy measured in preference for the correct form, regardless of whether the correct form is continuant- or stop-initial (synchronically, neither is the source of the other, because there are no underlying-to-surface derivations in this approach). Under this approach, we would similarly not expect processing of the continuant-initial verb roots (*-l̪iɲ*, *-waɭaŋi*, and *-waɭpumana*) to differ from the vowel-initial verb root *-aajuu*.

Under a rule-based analysis, by contrast, morphophonological rules are activated by the phonological shape of the selected morphemes and the context in which they occur; this is the case whether the derivation is serial—as in standard generative phonology of Chomsky and Hallé (1968) and the processing model of Levelt (1989) and Levelt et al. (1999)—or parallel and constraint-based as in Optimality Theory (Prince & Smolensky, 1993). This would lead us to predict an asymmetrical effect of conditioning frame, since applying a rule—here, transforming a continuant into a place-matched stop—would likely consist of an additional processing step—and this would have associated increased cognitive cost—which might reduce accuracy. Due to the cognitive cost of rule application, we would also argue that rule-based or dual-route approaches would predict that extra processing time—here, in the form of a 500 ms inserted pause—would lead to improved performance. We might also expect that a dual-route approach might predict difference in performance between the three continuant-initial verb roots (*-l̪iɲ*, *-waɭaŋi*, and *-waɭpumana*) and the vowel initial verb root *-aajuu* as the former are more easily handled by general rule application (the hardening rule is entirely exceptionless and productive in Wubuy; Nyhuis, 2023). This is because the selection of *-aajuu* vs. *-kaajuu* does not technically constitute hardening, as there is no continuant consonant onset to harden, and it might instead involve a listing of two alternate forms in the lexicon (as per Gaelic: Ussishkin et al., 2017), for reasons we discuss in Section 2.3.

2.2 Results for verb roots -l̪iɲ, -waɭaŋi, and -walpumana

The descriptive results for the Wubuy participants' responses in the expected preference directions are presented in **Figure 1**. As expected, accuracy rates were higher in the phonological condition where no hardening is required, and accuracy in the 500 ms pause condition was slightly higher than in the no-pause condition. For inferential statistics, we fitted three generalised linear mixed-effects models (GLMMs, binomial link) for the response data, see **Table 4**.

The random effects in these models controlled both participants (random intercepts and slopes) and lexis (random intercepts only). For fixed effects, Model 1 tested phonological condition; Model 2 tested both phonological condition and pause condition; and Model 3 tested both conditions as well as their interaction. Model performance was evaluated using the Akaike information criterion (AIC) score, where lower values indicate better fits. Among the three models, Model 2 had the lowest AIC score, so we interpret the preference pattern using this model.

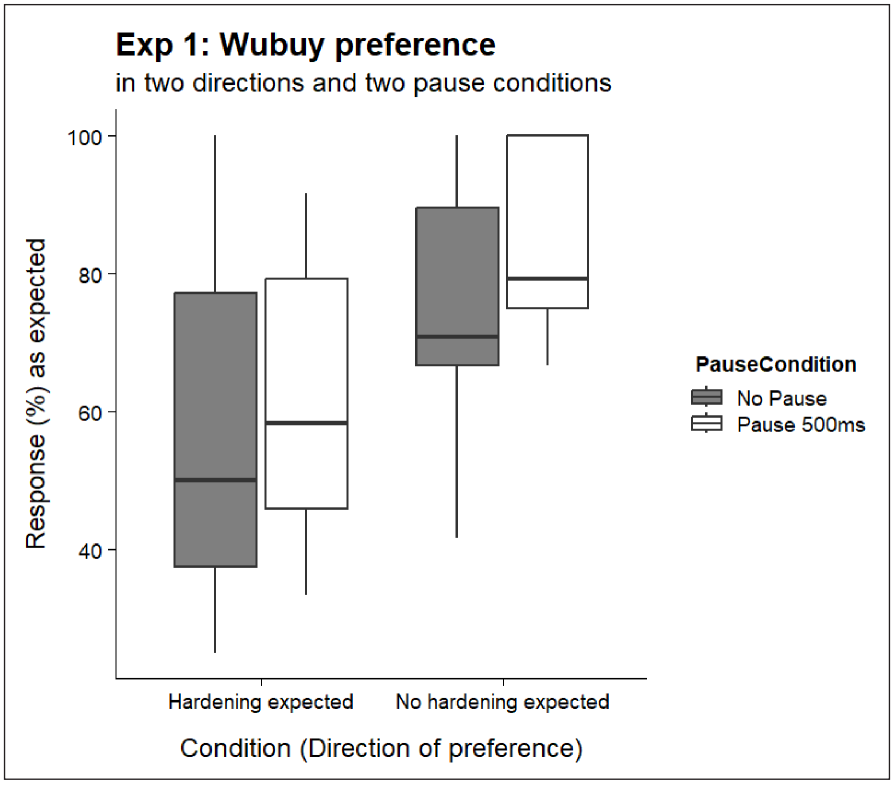

Figure 1: Median response rates in expected preference direction in Experiment 1.

Term	Model 1	Model 2	Model 3
Intercept (ref: Hardening *expected*)	0.425	0.216	0.306
Phonological = No hardening	1.231*	1.242*	1.042*
Pause = *500 ms*	–	0.428*	0.242
Interaction: Phonological × Pause	–	–	0.456
Evaluation: AIC score	548.7	546.8	547.7

Table 4: GLMM for Wubuy word preference in Experiment 1.

According to Model 2—formula: Score ~ Phonological Condition + Pause Condition + (1 + Phonological Condition | Participant) + (1 | Lexis)—the no-hardening context was a significant predictor of response rates ($\beta = 1.242$, $p = .0107$), as was the 500 ms pause condition ($\beta = 0.428$, $p = .0492$). The interaction between these two factors was not tested in the best-fit Model 2, but Model 3 indicated that it was not significant. Therefore, we carried out two separate *post hoc* comparisons for phonological condition and pause condition, which suggested that (a) the no-hardening context had significantly higher response rates in the expected directions (84%

vs. 61%, $p = .0053$) across two pause conditions, and (b) the 500 ms pause conditions had significantly higher response rates in the expected directions (78% vs. 70%, $p = .0246$) across two phonological conditions.

2.2.1 Results for verb root -aajuu

The experimental conditions for the vowel-initial verb root *-aajuu* were identical to those for the three continuant-initial verb roots (see **Table 5**). Participants' preference scores are presented in **Table 6**, along with *t*-tests against chance performance (50%), indicating that the Wubuy participants consistently preferred the predicted form (*-aajuu* vs. *-kaajuu*) in all four test conditions (correct response range 72.5-80%). A GLMM—formula: Score ~ Phonological Condition + Pause Condition + (1 + Phonological Condition | Participant)—however, revealed no effect of phonological condition (for frame requiring /k/-initial form *-kaajuu* versus frame requiring vowel-initial form *-aajuu*: Type II Wald Chi square = 0.0981, $p = 0.7541$), nor pause condition (no pause versus 500 ms of pause inserted: Chi square = 0.5938, $p = 0.4409$). This differs from the results for the three continuant-initial verb roots (*-l̪iŋ*, *-waɭaŋi* and *-waɭpumana*) for which we observed an effect of both hardening context (lower accuracy for trials requiring hardening) and pause insertion (improved performance with pause insertion).

Condition	Underlying form	Paired stimuli
Vowel-initial form expected	nuŋaak-waɳc**a**-aajuu	☞ [nuŋaapaɳcaajuu] (canonical) 💣 [nuŋaapaɳcakaajuu] (/k/-insertion over-applied)
/k/-initial form expected	nuŋaak-l̪arpi**c**-aajuu	💣 [nuŋaaṭarpicaajuu] (canonical: /k/-insertion under-applied) ☞ [nuŋaaṭarpickaajuu] (/k/-insertion applied)

Table 5: Sample experiment conditions for verb root *-aajuu* (☞ = expected response, 💣 = incorrect response). Each condition was presented with or without 500 ms pause inserted before the target.

Condition	Pause	Response %	SD	*p* value (50%)
/k/-initial form expected	No pause	77.5	24.9	.003**
	500 ms pause	75	11.8	< .001***
Vowel-initial form expected	No pause	80	25.8	.003**
	500 ms pause	72.5	24.9	.009**

Table 6: Preference data for vowel initial verb root *-aajuu* vs. *-kaajuu* (and testing the value against the 50% chance line, one-sample *t*-tests).

2.3 Discussion of Experiment 1: Phonological hardening

Experiment 1 tested the effect of correct and incorrect application of phonological hardening in a Two-Alternate Forced Choice (2AFC) experiment with speakers of Wubuy. The preference pattern from the analysis of the three continuant-initial verb roots (*-l̪iŋ*, *-waɭaŋi* and *-waɭpumana*) indicates that Wubuy speakers are much more accurate when no hardening is required than when hardening is required, and it further indicates that the occurrence of pause before the target verb root improves accuracy. We interpret these results as being consistent with the general predictions of rule-based, parsing accounts where verbs are listed in their underlying forms, whereas the hardened forms are derived based on phonological conditions in the complex word form. List-based accounts would have to attribute differences in accuracy to differences in the strengths of association or, perhaps, frequency differences between hardened and non-hardened (canonical) forms. However, given that hardening applies to approximately half of the verb lexemes in Wubuy and is productive and exceptionless, we find this account of the observed pattern less probable.

In contrast to the pattern observed for continuant-initial verb roots, Wubuy speakers are highly accurate in selecting the correct form of the vowel-initial root *-aajuu* ~ *-kaajuu regardless* of the context (/k/-insertion required or not): it is not as difficult to correctly select the stop-initial form as it is for the continuant-initial verbs. Also, in contrast to the continuant-initial verb roots, the results suggest that pause insertion does not improve performance.

Together, these observations suggest that phonological hardening of continuant-initial verbs might best be accounted for by application of a general rule (e.g., in standard feature-based rule formalism [+cont, –syll] → [–cont] / [–cont] _, i.e., "continuant consonants become non-continuant following non-continuants"), while parallel listings in the lexicon might better account for the alternation for vowel-initial roots like *-aajuu* in a mix-and-match type system reminiscent of the central idea in the Dual-Route Model (Ullman et al., 1997; Ullman, 2001, 2004). While all vowel-initial roots behave in the same way (having vowel-initial and /k/-initial forms, depending on phonological environment), there are differences between the continuant-stop alternations and the alternations of vowel-initial roots. In the first place, unlike the continuant-stop alternation, which is a response to a phonotactic violation which is universally observed in the Wubuy lexicon (Baker & Harvey, 2025: 183, 400), the vowel-stop alternation is not: there is no phonotactic problem which stop-insertion "fixes," in that intersyllabic sequences of non-continuant followed by vowel are unproblematic, phonotactically, unlike inter-syllabic sequences of non-continuant followed by continuant consonant, which are unlicensed in the Wubuy lexicon. A further added complication for these verbs is that in one morpho-phonologically specified condition, they instead have a /t/-initial form with a lengthened vowel in the first syllable, following the three nasal-final agreement prefixes *ŋan-* '1sg.irrealis', *nun-* '2sg.realis', and *nan-* '1st.inclusive.dual. irrealis' (which are also the only agreement prefixes conditioning hardening and *ŋu*-insertion,

discussed in the following section). Therefore, the alternants that speakers need to control for these verbs are both greater in number and not entirely phonologically conditioned, unlike the alternation between consonantal continuants and stops. We suggest that this may be behind the difference in behavior observed between these two kinds of verb alternation.

3. Experiment 2: *ŋu*-insertion

Experiment 2 examines the process of *ŋu*-insertion—the insertion of the meaningless syllable */ŋu/* before morphemes beginning in an underlying stop, if that morpheme follows a set of environments which have both morphological and phonological conditions—as illustrated in bold in Example (4). As detailed above, *ŋu*-insertion operates in parallel to the hardening rule examined in Experiment 1 and can be conceptualised as a grammatical device that signals to the listener—upon hearing and recognising */ŋu/*—that they should expect to next encounter a stop-initial morpheme, in particular a stop that is underived (underlying) and not a stop that is the outcome of hardening, even though the normal context *nuŋaa-* would elicit hardening of a continuant-initial morpheme in this position (Bentum et al., 2019). This difference is illustrated in (7). In the (a) form, the verb is underlyingly continuant-initial, but it must occur in its matched stop-initial variant following the prefix *nuŋaa-* because the Benefactive prefix conditions hardening even though it is never stop-final at the surface (this is thus an *opaque* conditioning context, in the sense of Kiparsky, 1971), as discussed in Section 2.1.2. In the (b) form, the verb is underlyingly stop-initial, and following the Benefactive prefix the string /ŋu/ must occur between the Benefactive and the verb.

(7) a. [nuŋaa**p**aɭaŋi] Expected surface form
/nuŋu-aak-**w**aɭaŋi/ Underlying form
2sgS/3sgFEMO-BEN-paint.PAST.CONT
'You painted (something) for her'

b. [nuŋaa**ŋu**paḷuɲ] Expected surface form
/nuŋu-aak-paḷuɲ/ Underlying form
2sgS/3sgFEMO-BEN-cut.PAST.PUNC
'You cut (something) for her'

Experiment 2 allows us to examine the preference patterns for combinations of prefix frames */nuŋaa-ŋu-/* and */nuŋaa-/* and six verbs in (underlying) continuant/vowel initial forms and in hardened forms, as well as preferences for stop-initial verbs and those same verbs in a mispronounced form (a single-feature mispronunciation, corresponding to a reversal of the hardening rule). This allows us to assess the strength of preference for correct forms, whether *ŋu*-insertion is required or not. It also allows us to examine rejection patterns for grammatically incorrect but attested forms, and mispronounced forms that differ phonologically from the

attested forms in a similar fashion, as hardened forms differ from (underlying) continuant/vowel initial forms. This is crucial to test the differential predictions made by full listing and associative models, and rule-based and dual-route approaches to processing. Full listing/associative models would generally predict strong preference only for correct forms and rejection of all incorrect forms, while rule-based/dual-route models might similarly predict strong preference for correct forms, but likely gradient levels of rejection for incorrect forms in a manner that reflects the type of "error" encountered. It is also crucial to test this because it may shed light on whether a correct/attested form can be either reverse engineered from the input or not, or whether a mispronunciation can be repaired.

3.1 Method

3.1.1 Participants

Prior to the passing away of the woman who produced the stimuli for both Experiment 1 and Experiment 2, eight of the 10 participants who *successfully* completed Experiment 1 also completed Experiment 2. As data was collected over several fieldtrips, each of the eight participants completed the second experiment on a different day (or even week, month, or year) than Experiment 1, but under identical testing conditions in a quiet home in Numbulwar or Darwin. We recognize that it is atypical to present experimental data with just eight participants, but as discussed in Section 2, the eight participants included in the experiment likely represent >15% of the speaker population, providing some confidence that their performance is representative of the Wubuy speech community.

3.1.2 Materials

The complex word stimuli for Experiment 2 were developed in collaboration with the same literate Wubuy speaker (female, in her 50s), who consulted on Experiment 1 and used similar complex word stimuli though lacking the incorporated nouns of Experiment 1. All target words (see **Table 7**) in Experiment 2 consisted of either the complex benefactive prefix frame *nuŋaa-* ('you/her.BEN') or the frame *nuŋaa-ŋu-* (also 'you/her.BEN', with insertion of meaningless *ŋu-,* indicating that the following morpheme begins in an underlying stop). Each of these prefix frames was followed by one of six verbs. The verbs included three vowel/continuant-initial verbs *-aajuu* 'to cut (Past Continuous)', *-waɭaŋi* 'to paint (Past Continuous)', and *-waɭpumana* also 'to paint (Present)' from Experiment 1, and their phonologically k-initial or hardened counterparts *-kaajuu*, *-paɭaŋi* and *-paɭpumana*. We also included three stop-initial verbs *-paḻuŋ* 'cut (Past Punctual)', *-pinimaŋ* 'hide (Past Punctual)', and *-culupana* 'put something behind (Present)', paired with three non-attested 'pseudo-lenited' forms: **-**w**aḻuŋ*, **-**w**inimaŋ*, and **-**j**ulupana* ('pseudo-lenited' phoneme in bold). In some sense, these non-attested 'pseudo-lenited' forms represent a reversal of the hardening rule. Their inclusion allows us to test the proposal that speakers of Wubuy operate with pairs of

morphemes differing in the value of [±continuant] of the initial segment (as in Nyhuis, 2023). In addition, it allows us to test the hypothesis that in a condition requiring a following stop (as is the case with both frames here in a classic neutralisation context), participants may not perceive the [±continuant] contrast.

Prefix	Verbs	Underlying onset
nuŋaa-	*-aajuu*, *-kaajuu* 'to cut'	vowel
nuŋaaŋu-	*-waɭaŋi*, *-paɭaŋi* 'to paint'	continuant
	-waɭpumana, *-paɭpumana* 'to paint'	continuant
	-paɻuɲ, **-**w**aɻuɲ* 'cut'	stop
	-pinimaɲ, **-**w**inimaɲ* 'hide'	stop
	-culupana, **-**j**ulupana* 'put behind'	stop

Table 7: Overview of the morphological composition of the target words in Experiment 2a and 2b. An asterisk * indicates that the form is a non-attested mispronounced verb, the pseudo-lenited phoneme in bold. Both frames *nuŋaa-* and *nuŋaaŋu-* require a stop to follow, though with different derivational history. The underlying stop-initial verbs require the *nuŋaaŋu-* frame, while the hardened verbs require the *nuŋaa-* frame.

The stimuli for Experiment 2 were recorded by the same Wubuy speaker who consulted on the experiment and who also provided recordings and consultation for Experiment 1. The stimuli were recorded using a PMD660 Marantz flash-RAM digital recorder with a DPA d:fine headset microphone, at a 16-bit sampling depth and a sampling rate of 44.1 kHz. During the recording session, the speaker produced the two carrier frames *nuŋaa-* and *nuŋaaŋu-* followed by pause, in which she *imagined* producing a verb stem. The speaker also produced the six target verbs in two forms with phrase final intonation: the three continuant-initial verbs were also elicited in their hardened form, and the three stop-initial verbs were also elicited in a mispronounced, non-existent pseudo-lenited form. One token of each frame type, as well as one instance of each form of the six verbs, was selected based on similarity in pitch and volume, individually normalized, and cross spliced in *Praat* (Boersma & Weenink, 2014). This procedure created two sets of 12 word-pairs (12 for Experiment 2a and Experiment 2b, respectively).

Verbs that begin in stops underlyingly (e.g., when following vowels) require */ŋu-/* to precede them in the context of (abstract or actual) stop-final prefixes such as *nuŋaa-*; thus *nuŋaaŋu-pinimaɲ* 'we hid (something) from her' is ungrammatical in Wubuy. Conversely, the prefix form *nuŋaaŋu-* is ungrammatical when it precedes underlying continuant-initial verbs like *waɭaŋi* 'paint (PastCont)', but hardening is required following the prefix *nuŋaa-*, as explained in the previous experiment, thus *nuŋaa-paɭaŋi* 'we painted (something) for her' and **nuŋaa-waɭaŋi* is ungrammatical. In other words, following the Benefactive prefix *nuŋaa-,* all verbs must be

stop-initial at the surface, but those that are *underlyingly* stop-initial must additionally take */ŋu-/* between the prefix and the verb.

3.1.3 Procedure

Experiment 2 followed the same procedure as Experiment 1. To prevent participants working out which variables were being manipulated in each of the two experiment halves (frame versus target verb), all 24 individual word-pairs were presented in one pseudo-randomized experiment, with order of presentation of each trial counterbalanced, generating a total of 48 pseudo-randomised trials. As this experiment took much longer to complete than Experiment 1 and was perceived to be more difficult, participants were offered a break halfway through the experiment.

3.2 Experiment 2a: Frame effects

3.2.1 Experiment 2a predictions

As detailed above, Experiment 2a required participants to indicate their preference for utterances that differed only in the frame (*nuŋaa-* versus *nuŋaaŋu-*) and provided grammatically correct options in 50% of trials (Example (b) and Example (c) in **Table 8**, below). In the other 50% of trials, participants had a choice between ungrammatical utterances with either attested (continuant-initial) verb forms or un-attested mispronounced verb forms, differing only in the presence or absence of *ŋu-*, as illustrated in **Table 8**. As **Table 8** indicates, trials with vowel- or continuant-initial verbs (*-aajuu*, *-waɭaŋi*, *-walpumana*) are always ungrammatical and differed in whether *ŋu-* was (also) oversupplied, while the trials with the corresponding /k/-initial or phonologically hardened verbs (*-kaajuu*, *-paɭaŋi*, *-palpumana*) are always grammatical in the *nuŋaa-* frame. Trials with (underlyingly) stop-initial verbs (*-paḷuŋ*, *-pinimaŋ*, and *-culupana*) are always grammatical in the *nuŋaaŋu-* frame, while mispronounced pseudo-lenited verbs (**-waḻuŋ*, **-winimaŋ*, and **-julupana*) offered non-attested lexical forms with or without oversuppliance of *ŋu-*.

Onset type	Frame 1: *nuŋaa-*	error type	Frame 2 *nuŋaaŋu-*	error type
a. continuant	*-waɭaŋi*	hardening under-applied	*-waɭaŋi*	oversupplied *ŋu-* 💣
b. hardened	***-paɭaŋi***		*-paɭaŋi*	oversupplied *ŋu-* 💣
c. stop	*-pinimaŋ*	undersupplied *ŋu-* 💣	***-pinimaŋ***	
d. pseudo-lenited	**-winimaŋ*		**-winimaŋ*	oversupplied *ŋu-* 💣

Table 8: Examples of Experiment 2a trial types. Correct trials in bold. 💣 indicates */ŋu-/* error.

Under associative (Goldberg, 1995; Jackendoff & Audring, 2020) and full listing models (Baayen et al., 2011; Gonnerman et al., 2007; Plaut, 2011; Rueckl et al., 1997; Rumelhart & McClelland, 1986; Westermann & Ruh, 2012), where linearity is assumed and onset variance is accounted for by the activation of available non-derivational, parallel structures, the correct forms are selected in a one-step process from multiple equivalent forms. This means that we would assume that the frame (*nuŋaa-* or *nuŋaaŋu-*) activates a particular subset of suitable verb forms in the listener's mind and that recognition requires "clipping together stored pieces in such a way that every element of the composed structure is accounted for in terms of one stored piece or another" (Jackendoff & Audring, 2020, p. 4). This process presumably allows for processing of novel input by analogy (what is this input most like?), though it is not clear how analogy might be measured (a well-known problem in historical linguistics, see Anttila, 1989, p. 94). In the present context, associative and full listing approaches would predict an overwhelming preference for *nuŋaaŋu-* frames preceding (underlyingly) stop-initial verbs and a similarly strong preference for *nuŋaa-* frames preceding hardened verbs, as these are the attested forms. All other combinations (regardless of error type) would be disfavored, leading to an expectation of chance performance for these combinations (where neither frame is acceptable).

Under a (generativist) rule-based approach, correct forms are similarly preferred, but early utterance planning must select the intended prefix as well as the intended verb from the lexicon, and once those have been selected, verb onset must be examined to determine whether it is a candidate for hardening (e.g., following a non-continuant consonant), or whether the verb is an underlying stop-initial form, in which case */ŋu-/* must be activated and inserted before the string is successfully recognized (or produced) (c.f. Levelt, 1989, p. 284; Kilbourn-Ceron & Goldrick, 2020).

Predictions based on a rule-based approach might, however, differ from predictions from a parallel-associative approach with respect to listener frame preferences preceding mispronounced verbs (e.g., **-winimaŋ*) and continuant-initial verbs (e.g., *-waɭaŋi*), neither of which is acceptable in either of the frames. Here, a rule-based approach might predict a preference for *nuŋaaŋu-* frames in conjunction with mispronounced verbs (e.g., **-winimaŋ*), if these are recognised as one-feature mispronunciations of familiar stop-initial verbs and result in activation of the appropriate verb. A factor which could potentially promote this interpretation is that none of these mispronunciations matches an existing verb in the lexicon (and indeed, this is generally the case in Wubuy: Nyhuis, 2023, p. 96). This would result in more gradient difference in the patterns of acceptability of the non-attested forms (Gaskell & Marslen-Wilson, 1996; 1998; Gow, 2001; Ranbom & Connine, 2007). By contrast, the legitimate continuant-initial verbs can't be interpreted as mispronunciations of stop-initial forms, because replacing the initial segment with a place-matched stop doesn't produce an existing verb. In this case, chance performance would be expected (because neither selection is grammatical).

3.2.2 Experiment 2a results and discussion

Experiment 2a tested the preference of *ŋu*-insertion with four types of target verbs:

1. verbs beginning in faithful stops (underlying stops that are realised as stops);
2. verbs beginning in faithful continuants (underlying continuants that are realised as continuants);
3. verbs beginning in stops that are the result of phonological hardening (underlying continuants that have hardened to stops at the same POA, as per Experiment 1); and
4. mispronounced verbs (verbs in which a stop onset is realised as a continuant phoneme with the same POA; a one-feature deviation).

The descriptive statistics are presented in **Figure 2**, calculated as participant preference for *nuŋaaŋu-* frames over *nuŋaa-* frames.

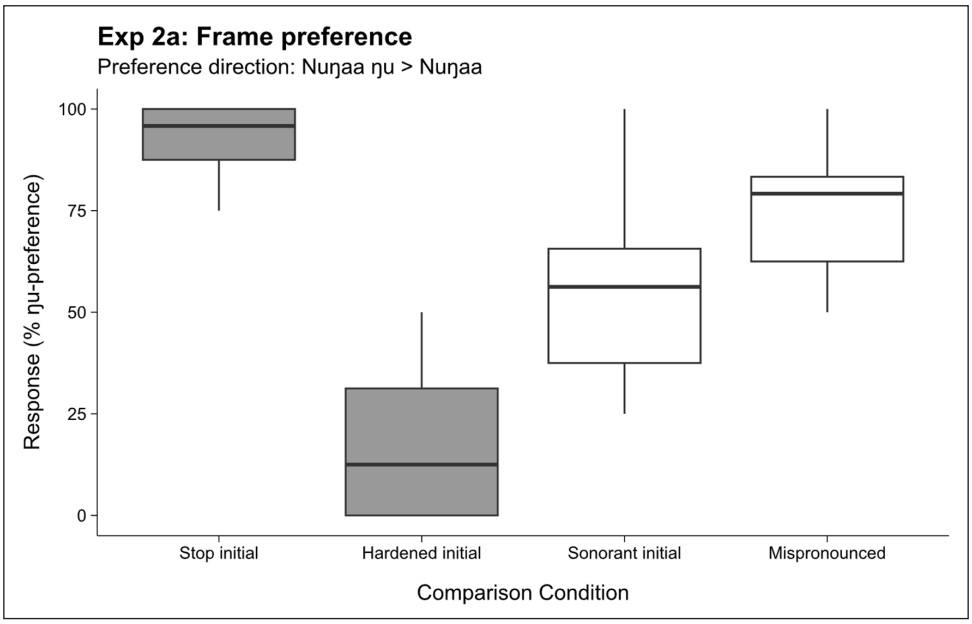

Figure 2: Median response rates favouring *ŋu*-insertion in different verb-initial conditions. Grey boxes indicate grammatical forms; white boxes indicate ungrammatical forms. Box edges represent 25% and 75% percentiles, respectively.

Before comparing the response percentage data among the four conditions, we tested the mean value against the chance level (50%) using one-sample *t*-tests. These results showed that the response rate in the stop-initial condition is significantly higher than the chance level ($M = 93\%, p < .001$), while the rate in the hardened initial condition was significantly lower than the chance level ($M = 17\%, p = .004$). The faithful continuant-initial condition led to chance-level

performance (M = 57%, p = .487), and the response rate in the mispronounced verb condition was significantly higher than 50% (M = 76%, p = .006), indicating that participants had clear frame preferences in all conditions but the continuant-initial condition.

For between-condition comparisons, we built a GLMM—formula: Score ~ Condition + (1 | Participant)—and carried out mean value comparisons. Consistent with the descriptive pattern and also with the *t*-tests against chance performance, the GLMM showed that the preference rates for frame with *ŋu*-insertion were highest before stop-initial verbs, followed by mispronounced stop-initial verbs. The preference pattern for continuant-initial verbs was close to chance, and finally, the *nuŋaaŋu-* frame was strongly dispreferred in conjunction with verbs with hardened initial stops (17%), the context in which a strong preference for the *nuŋaa-* frame was expected. *Post hoc* tests showed that all pairwise comparisons were significant ($p < .008$ for five comparisons, Tukey adjustment), except for between mispronounced verbs and continuant-initial verbs, i.e., stop-initial verbs > mispronounced verbs ≥ continuant-initial verbs > hardened initial verbs.

Together, these results demonstrate that participants prefer grammatically correct sequences, as would be expected under both PA and rule-governed approaches: stop-initial verbs were preferred with *nuŋaaŋu-* frames, while hardened (underlyingly continuant-initial) verbs were preferred with *nuŋaa-* frames. Importantly, the results also suggest that mispronounced and continuant-initial verbs make frame selection more difficult for participants, though not to the same degree. On one hand, participants' preference pattern was at chance level for frame selection for continuant-initial verbs in trials where neither frame option offered a grammatically correct result, suggesting that the participants found both options unacceptable. By contrast, the frame preference patterns for continuant-initial and mispronounced verbs differed, suggesting that mispronounced verbs were still recognisable—or at least plausibly interpreted as the right words spoken incorrectly and thus preferred—whereas the continuant-initial verb was considered equally unacceptable in either frame (Altvater-Mackensen & Mani, 2013). This option was apparently not available in the case of actual continuant-initial verbs: these cannot be interpreted as mispronounced stop-initial verbs, probably because they are existing lexical items. This is consistent with our computational predictions of gradient acceptability rates for different types of unattested forms.

3.3 Experiment 2b: Onset preference patterns

3.3.1 Experiment 2b predictions

While Experiment 2a examined the effect of *prefix frame*, Experiment 2b examines the effect of verb onset alternations *within* each of the two prefix frames (*nuŋaa-* and *nuŋaaŋu-*) (see **Table 9**). Experiment 2b thus held the carrier frame constant and tested preference for verb onsets within a single frame (*nuŋaa-* or *nuŋaaŋu-*). It comprised six word-pairs beginning with *nuŋaa-* and

six word-pairs beginning with *nuŋaaŋu-* followed by each of the six verbs (three continuant/vowel-initial verbs and three stop-initial verbs), each paired with its respective hardened or mispronounced forms. In the *nuŋaa-* frame, hardened verbs provided grammatically correct options, while stop-initial verbs provided grammatically correct options in the *nuŋaaŋu-* frame.

Based on both parallel-associative style and rule-based generative frameworks, we would expect the Wubuy participants to show strong preference for correct forms (hardened verbs in the *nuŋaa-* frame and stop-initial verbs in the *nuŋaaŋu-* frame). Under associative frameworks, we would expect all incorrect/unattested sequences to be rejected, resulting in a no-preference pattern (chance), while we might expect gradient preference patterns under rule-based and dual-route models as differences in error type (e.g., mispronunciation vs. incorrect hardening vs. continuant/vowel initial).

Frame	Verb 1	Onset	Verb 2	Onset
nuŋaa-	-waɭaŋi	continuant-initial	**-paɭaŋi**	correctly hardened continuant
	-*winimaɲ	mispronounced	-pinimaɲ	stop-initial
nuŋaaŋu-	-waɭaŋi	continuant-initial	-paɭaŋi	hardened continuant
	-*winimaɲ	mispronounced	**-pinimaɲ**	correct stop-initial

Table 9: Examples of Experiment 2b trial types. Correct trials in bold. * indicates mispronounced non-attested form.

3.3.2 Experiment 2b results and discussion

Experiment 2b tested the preference for stop and continuant verb onsets (hardened stops versus underlying continuant-initial verbs; stop-initial versus unattested mispronounced verbs) in both the *nuŋaa-* and *nuŋaaŋu-* frames. We present the descriptive response rates in **Figure 3**.

As we did in Experiment 2a (Section 3.2), we first tested the preference response rates against the 50% chance level in a series of one-sample *t*-tests. Note that within each frame (*nuŋaa-* versus *nuŋaaŋu-*), one trial type offered no correct answers (participants had to select between two *incorrect* forms that differed in the type of error they represented), and one trial type offered a grammatical choice. Importantly, in both cases, the phonological difference between the two available forms was a single-feature deviation between a stop and a continuant at the same POA (or a vowel-initial vs. /k/-initial form, in the case of *-aajuu* ~ *-kaajuu*).

In the *nuŋaa-* frame, the tests against chance showed that the participant preference scores were above chance for the correctly hardened > continuant-initial direction (M = 73%, p = .018), as well as for the stop-initial > mispronounced (M = 74%, p = .008), indicating a dis-preference for mispronounced items and a preference for stops, even though the stop-initial form

was not preceded by the grammatically obligatory */ŋu-/*, consistent with rule-based predictions of differential tolerance for error types. In the *nuŋaaŋu-* frame, the preference pattern was at chance level in the hardened > continuant-initial condition (M = 59%, p = .423, where neither form is grammatical), consistent with both rule-based and parallel-associative predictions in Section 3.3.1. Lastly, again as expected under both theoretical approaches, results were significantly above chance in the grammatical stop-initial > mispronounced trials (M = 88%, p < .001), indicating a strong preference for grammatical over mispronounced verbs.

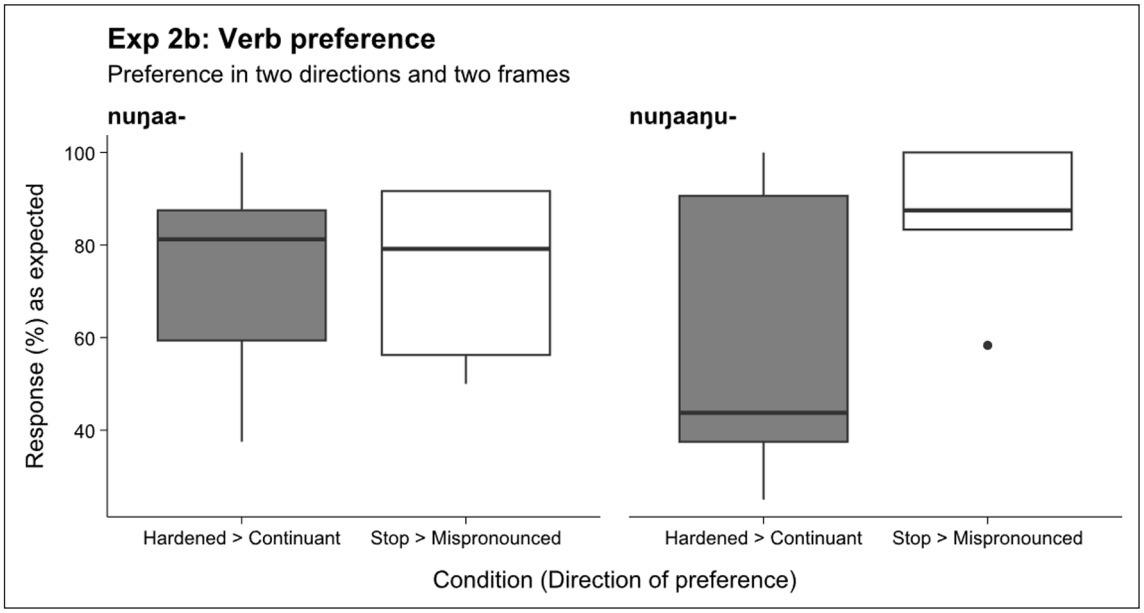

Figure 3: Median verb onset preference pattern in the *nuŋaa-* and *nuŋaaŋu-* frames. Box edges represent 25% and 75% percentiles, respectively.

For between-condition comparisons, we fitted a confirmatory GLMM—formula: Score ~ Frame * Condition + (1 + Condition | Participant) + (1 | Stimulus Sentence)—which revealed a significant interaction effect between Frame and Condition (Chi-squared = 6.11, p = .013). Consequently, we carried out *post hoc* tests within each frame. In the *nuŋaa-* frame, these comparisons showed that the preference for the grammatically incorrect but attested stop-initial verb over mispronounced verbs was as strong as the preference for grammatically correct hardened verbs over continuant-initial verbs (p = .770), suggesting that participants have a lower tolerance for mispronunciations (the pseudo-lenited form) than ungrammaticality (the stop-initial form in an ungrammatical *nuŋaa-* frame). This again is consistent with the predictions of computational models. In the *nuŋaaŋu-* frame, participants strongly and unsurprisingly preferred the correct stop-initial verb over mispronounced verbs but found the two grammatically incorrect verb forms (hardened versus continuant-initial) unacceptable (p = .017), consistent with their

chance preference pattern. This is consistent with parallel-associative and full listing predictions, and likely also with computational approaches.

Finally, we compared each verb pairing *between* frames. This comparison showed a preference for hardened verbs over the continuant-initial verbs in both the *nuŋaaŋu-* and *nuŋaa-* frames (preference difference n.s. at $p = .132$), indicating that participants recognised that a hardened verb form is required following *nuŋaa-*, even when a superfluous and grammatically incorrect */ŋu-/* is inserted. This is not consistent with the predictions of parallel-associative models, where unattested forms should be rejected, not repaired. Between-frame comparisons of preference for stop-initial > mispronounced verbs showed a stronger preference for stop-initial verbs over mispronounced verbs when */ŋu-/* was inserted ($p = .042$), i.e., in the grammatically correct frame. This indicates that mispronunciation may make lexical decision more difficult, but not impossible (Altvater-Mackensen & Mani, 2013), again producing a gradient outcome that is not readily reconcilable with associative and full-listing models. And it suggests that it is easier to process *one* mistake (mispronunciation) than *two* mistakes (mispronunciation *and* a missing */ŋu-/*), an additive view of processing difficulties consistent with generative approaches but less straightforwardly accounted for by linear associative paradigms. Together, based on the results from Experiment 2b, we tentatively suggest that processing of *ŋu*-insertion in conjunction with different verb forms (continuant-initial, verb-initial, hardened and mispronounced verbs) can disrupt word processing in ways that are difficult to account for with models of word recognition that rely on linear, associative paradigms, transitional probabilities, and activation of parallel stored lexical items in a speaker/hearer's mind.

4. General discussion

The present paper examines the processing of two linked morphophonological alternations—phonological hardening and *ŋu*-insertion—in the Australian Indigenous language Wubuy. The studies probe the crucial theoretical question of whether such linguistic phenomena are better conceptualised as morpho-lexical parallel-associative processes (e.g., Construction Morphology: Booij, 2018; Relational Morphology: Jackendoff & Audring, 2020), should instead be accounted for by rule-governed processes on underlying forms (e.g., Chomsky & Halle, 1968), or perhaps whether both memory- and rule-based processing (Ullman et al., 1997; Ullman, 2001; 2004) are necessary to account for speaker behavior.

Experiment 1 (Section 2) tested the effect of over- and under-application of phonological hardening on word recognition in a two-part 2AFC experiment (Experiment 1a, 1b). Each trial required participants to indicate preference between word pairs where hardening was correctly applied in half, and under-applied or over-applied (i.e., with/without a preceding non-continuant segment, respectively) in the other half. Experiment 1a and Experiment 1b differed only in whether a brief pause (500 ms) had been inserted before the target verb. The results, excepting

the special case of *-aajuu* and its stop-initial counterpart *-kaajuu*, indicate that it is easier for Wubuy speakers to correctly select non-hardened verbs in non-hardening contexts than it is for them to correctly select hardened verbs in a hardening context, and that extra processing time (here, pause insertion) improves accuracy, in line with the rule-based predictions in Section 2.1.4. Overall, this pattern of behavior—increased difficulty in one direction and improvement in accuracy due to pause insertion—is consistent with the predictions of rule-based approaches. It suggests that the lexicon only stores canonical (non-hardened) forms, with the exception, perhaps, of vowel-initial verbs—in this case, the insertion of an onset consonant attains the correct surface form. The results presented here are more consistent with an account where the correct form is selected using declarative memory.

Experiment 2 (Section 3) examined the process of *ŋu*-insertion—the insertion of the meaningless string */ŋu-/* before morphemes beginning in an underlying stop—under complex conditions but including where the preceding morpheme ends in an underlying or surface stop, as is the case with the complex transitive Benefactive prefix *nuŋaa-*. Experiment 2a (Section 3.2) tested the preference for *ŋu*-insertion with four types of target verbs: verbs beginning in faithful stops, verbs beginning in faithful continuants, verbs beginning in phonologically hardened stops, and mispronounced, pseudo-lenited verbs.

The results from Experiment 2a (unsurprisingly) demonstrate that participants prefer grammatical sequences, as would be expected under parallel-associative and rule-governed approaches, but also that different types of errors induce different levels of rejection, which, we argue, reflect participant knowledge of multilevel processes of word formation. A clear example of this is that preference patterns *differ* for the two verb forms (the continuant-initial verbs and the mispronounced verbs) that are ungrammatical with both prefix frames. While participants clearly prefer the frame that would be grammatical for the *mispronounced* form if it were pronounced with an initial stop (76% preference for the *nuŋaaŋu-* frame), frame preference for the *continuant-initial* form is at chance, even though ignoring the continuancy of the initial segment (and pretending it is a stop, as with the mispronounced form) would give a grammatical result in the *nuŋaa-* frame). This suggests that listeners prefer to ignore a single-feature mispronunciation to ensure grammaticality for the *mispronounced* forms (preferring mispronounced forms in the correct *nuŋaaŋu-* frame), because by doing so, they can arrive at a grammatical form (with an underlying stop). By contrast, participants are *not* willing to ignore a single-feature mispronunciation in the form of an unhardened continuant-initial form in the *nuŋaa-* frame (it is deemed a no better choice than the double-error option offered by the *nuŋaaŋu-* frame). This suggests the existence of two different processes in dealing with these inputs (continuant-initial and mispronounced). In the continuant-initial input, speakers recognize the verb morpheme, but neither frame produces a grammatical result, giving them no good options. In the mispronounced input, speakers fail to find a match with an existing morpheme, and no morphophonological rule is available to

transform the input into an underlying form, which perhaps licenses their inference that it is mispronounced, but not necessarily ungrammatical.

Experiment 2b (Section 3.3) tested the preference for stop and continuant-initial verb onsets (hardened stops versus underlying continuant-initial verbs; stop-initial versus unattested mispronounced verbs) in both the *nuŋaa-* and *nuŋaaŋu-* frames. The results show—again unsurprisingly—that the Wubuy participants prefer inputs in the correct grammatical form, but the results also indicate that the participants are willing to accept canonical verb forms when they are presented in an *ungrammatical* context. This latter result indicates that the preceding context does not preclude preference for verbs whose shape is not licenced by the context when the alternative choice—despite having a suitable form—cannot be converted (by rule application or other mechanism) into a meaningful selection from the lexicon. Therefore, we cautiously suggest that parallel-associative approaches relying on a listener *"clipping together stored pieces in such a way that every element of the composed structure is accounted for in terms of one stored piece or another"* (Jackendoff & Audring, 2020, p. 4; our emphasis) may not adequately account for the observed behavior.

In their totality, the results from Experiment 1 (hardening) and Experiment 2 (*ŋu*-insertion) presented here suggest that the twin phenomena of phonological hardening and *ŋu*-insertion in the Australian Indigenous language Wubuy (Heath, 1984) are better accounted for as multi-step, rule-based processes, as the results are consistent with a Wubuy lexicon where verbs are listed in a single form. For continuant-initial verbs, this means they do not have a stop-onset parallel listed form that is activated when words and phrases are, to paraphrase Jackendoff and Audring (2020), "clipped together" in a manner that accounts for all elements and on the basis of frequency and distributional patterns. Rather, as illustrated by the results of Experiment 1, that hardening is the result of a rule-based process, one that increases the cognitive load and increases the error rate.

For stop-initial verbs, only a single lexical entry is assumed and preference for the grammatically correct *nuŋaaŋu-* frame is high and very consistent in Experiment 2a. Participants also confidently prefer the grammatically correct *nuŋaaŋu-* frame (rather than incorrect *nuŋaa-*) even when stop-initial verbs are produced with a single-feature onset mispronunciation as a continuant. Participants' equally strong preference for correctly produced stop-onset verbs over mispronounced forms in Experiment 2b demonstrates that mispronunciation tolerance is not due to stop-continuant phonological neutralisation following */ŋu-/*, though introduction of a grammatical error (undersupplied */ŋu-/*), also in Experiment 2b, shows that increased processing demands in the form of a grammatical mismatch increases participant tolerance for the mispronounced forms (a reduction in accuracy from 88% to 74%).

Under parallel-associative models of morphology, as well as linear models of continuous parsing like the Cohort Model (Marslen-Wilson & Welsh, 1978), TRACE (McClelland & Elman, 1986) and Shortlist B (Norris & McQueen, 2008), the effect of frame on verb preference is

important, as correct selection of upcoming elements from parallel listings in the lexicon is contingent on what has already been presented. Under these models, *nuŋaa-* is presumably processed *first*. A listener *then* either:

(1) identifies */ŋu-/* and *then* proceeds to select a verb form from those verbs in the lexicon that have only one (stop-initial) entry listed, *or*,

(2) proceeds directly to select a stop-initial verb form from those lexical entries that have two parallel listed forms, one of which is stop-initial (hardened) and one of which is continuant/vowel initial.

Given that the requirement of *ŋu-* is not determined by the prefix alone but by the prefix in combination with the onset of the verb, it is not possible for speakers to determine whether */ŋu-/* is required, however, until verb-selection is complete. This challenges the linearity of the process, unless one wishes to argue that all stop-initial verbs are *also* dual-listed, with a form starting in */ŋu-/* (though see Nyhuis, 2023 p. 106, for an alternative position).

Rather, the data presented here is consistent with an approach to word recognition in which phonological hardening and *ŋu*-insertion are processes that occur after all lexemes have been selected, as in Levelt's classic processing model (1989). Under this approach, prefix and verb selection precede the application of any morphophonological rules (hardening or *ŋu*-insertion), which are triggered only by the *phonological form* of the selected item, once the item has been selected. Where a rule is triggered, it activates a secondary process, incurring additional processing costs, which presumably can be quantified in the form of reaction time and accuracy measures, as demonstrated here.

The data presented here does not, however, suggest that *all* processes must be rule governed, and that parallel listings and associative patterns cannot account for some aspects of language processing, including some aspects of the complex Wubuy morphophonology that we are discussing here. Indeed, some of the data presented here, as in the case for the alternations in vowel-initial verbs like *-aajuu*, is better accounted for by exactly the kind of memory and listings-based approach advocated for in parallel-associative models, and we encourage consideration of models of word recognition that allow associative/listings-based explanations of some phenomena and rule-based explanations for others in an integrated fashion (Ullman et al., 1997; Ullman, 2001, 2004). However, the results also suggest that parallel-associative and Constructionist approaches would need additional architecture to explain why (a) some grammatical forms are apparently more difficult to select than others, and (b) why some unattested forms are better than others.

Finally, we wish to address the limitations of the present experiments. Experimental research on language processing in Wubuy is constrained by many factors, including language loss, an aging population, and substantial logistical difficulties associated with data collection in remote

parts of Australia. The effect of these constraints warrant discussion. First, our experimental designs and approaches consequently deviate from standard laboratory practices, as many traditional laboratory approaches are unsuitable for participants who require technical support and prefer to be tested in smaller social groupings. This means that the data collected is less controlled than is typically the case and that certain types of data that might have been highly informative (e.g., response times) cannot be collected meaningfully. Second, we acknowledge that the low number of participants, as well as the low number of experimental trials per participant, dramatically reduces the statistical power of our experiments, with consequences for the generalizability of the results. We have detailed the reasons for this elsewhere, and we would like to highlight again, that Experiment 1 tested 25% of the speaker population, while Experiment 2 tested approximately 15%. This is a very significant coverage of the population, akin to testing millions of speakers of Australian English in a study of the processing (or other phenomena) of that variety of English. We would also like to highlight that research using the experimental protocol employed here, along with similar participant numbers, has already contributed substantially to our understanding of language processing in Australian Indigenous languages (Bundgaard-Nielsen & Baker, 2020; Bundgaard-Nielsen et al., 2025). And in pursuit of hard-to-get experimental data, we encourage colleagues to employ whatever design is acceptable to the speaker population. More research of this kind will greatly benefit the research community and theory building, including theories of continuous parsing, as recognized in several recent overviews (Anand et al., 2011; Berghoff & Bylund, 2025; Norcliffe et al., 2015).

Research Data Availability Statement

The experiment and data collected here cannot be made generally accessible to the research public, under our ethics approval. All use of the experiments and data must be approved in consultation with the Wubuy-speaking community.

Acknowledgements

First and foremost, we thank Mrs. L. M., the Wubuy consultant and speaker for the two experiments presented here, who passed away before publication of this study. L. M. was an outstanding Indigenous language specialist and teacher. Her contribution to research, language preservation, and language revitalisation in Wubuy was substantial and will have long-lasting benefits to her community and to the research community alike. We also thank the Wubuy-speaking participants, including Mrs J. N., whose contribution to Wubuy language research, language preservation, and language revitalisation was similarly substantial and who has now also, sadly, passed away. We thank the wider community of Numbulwar for their kindness and hospitality. We thank Prof. Anne Cutler, whose enthusiasm for the phenomena examined here encouraged us to conduct these experiments and ensure their publication. We thank the Australian Research Council for funding the research as part of Discovery Project DP180100821, awarded to the first and second authors.

Competing interests

The authors have no competing interests to declare.

References

Altvater-Mackensen, N., & Mani, N. (2013). The impact of mispronunciations on toddler word recognition: Evidence for cascaded activation of semantically related words from mispronunciations of familiar words. *Infancy*, *18*, 1030–1052. https://doi.org/10.1111/infa.12022

Amenta, S., & Crepaldi, D. (2012). Morphological processing as we know it: An analytical review of morphological effects in visual word identification. *Frontiers in Psychology*, *3*. https://doi.org/10.3389/fpsyg.2012.00232

Anand, P., Chung, S., & Wagers, M. (2011). *Widening the net: Challenges for gathering linguistic data in the digital age* [White paper]. NSF project SBE 2020: Future research in the Social, Behavioral and Economic Sciences.

Anttila, R. (1989). *Historical and comparative linguistics*. John Benjamins. https://doi.org/10.1075/cilt.6

Baayen, R. H., Milin, P., Đurđević, D. F., Hendrix, P., & Marelli, M. (2011). An amorphous model for morphological processing in visual comprehension based on naive discriminative learning. *Psychological Review*, *118*(3), 438–481. https://doi.org/10.1037/a0023851

Baker, B. J. (2008). *Word structure in Ngalakgan.* CSLI Publications.

Baker, B. J., & Harvey, M. (2026). *The phonology and morphology of Australian languages*. Cambridge University Press. https://doi.org/10.1017/9781316411469

Ball, M. J., & Müller, N. (1992). *Mutation in Welsh.* Routledge.

Bentum, M., ten Bosch, L., van den Bosch, A., & Ernestus, M. (2019). Listening with great expectations: An investigation of word form anticipations in naturalistic speech. *Interspeech 2019: Proceedings of the 20th Annual Conference of the International Speech Communication Association* (pp. 2265–2269). https://doi.org/10.21437/Interspeech.2019-2741

Berghoff, R., & Bylund, E. (2025). Diversity in research on the psychology of language: A large-scale examination of sampling bias. *Cognition*, *256*, 106043. https://doi.org/10.1016/j.cognition.2024.106043

Blanco-Elorrieta, E., Gwilliams, L., Marantz, A., & Pylkkänen, A. (2021). Adaptation to mispronounced speech: Evidence for a prefrontal-cortex repair mechanism. *Scientific Reports 11*, https://doi.org/10.1038/s41598-020-79640-0

Blasi, D. E., Henrich, J., Adamou, E., Kemmerer, D., & Majid, A. (2022). Over-reliance on English hinders cognitive science. *Trends in Cognitive Sciences*, *26*(12), 1153–1170. https://doi.org/10.1016/j.tics.2022.09.015

Boersma, P., & Weenink, D. (2014). *Praat: Doing phonetics by computer* (Version 5.3.82) [Computer software]. http://www.praat.org.

Bohn, A., & Bundgaard-Nielsen, R. L. (2021). Not "WEIRD" but truly different: Cultural life scripts and autobiographical memory in Indigenous Australia. *Journal of Applied Research in Memory and Cognition, 10*(1), 85–94. https://doi.org/10.1016/j.jarmac.2020.09.006

Booij, G. (2018). *The construction of words: Studies in morphology* (Vol. 4). Springer. https://doi.org/10.1007/978-3-319-74394-3_1

Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2016). The importance of linguistic typology for the neurobiology of language. *Linguistic Typology*, *20*(3), 615–621. https://doi.org/10.1515/lingty-2016-0032

Brouwer, S., Mitterer, H., & Huettig, F. (2013). Discourse context and the recognition of reduced and canonical spoken words. *Applied Psycholinguistics, 34*(3), 519–539. doi:10.1017/S0142716411000853

Bundgaard-Nielsen, R. L., & Baker, B. J. (2014). Frequency in the input affects perception of phonological contrasts for native speakers. *Proceedings of the 15th Australasian International Speech Science and Technology Conference* (pp. 206–209).

Bundgaard-Nielsen, R. L., & Baker, B. J. (2016). Fact or furphy? The continuum in Kriol. In F. Meakins & C. O'Shannessy (Eds.), *Loss and renewal: Australian languages since contact* (pp. 177–216). Mouton de Gruyter. https://doi.org/10.1515/9781614518792-013

Bundgaard-Nielsen, R. L., & Baker, B. J. (2020). Pause acceptability indicates word-internal structure in Wubuy. *Cognition*, *198*, 104167. https://doi.org/10.1016/j.cognition.2019.104167

Bundgaard-Nielsen, R. L., Mailhammer, R., Baker, B. J., Wang, Y., Harvey, M., & Turner, C. (2025). Lenition, fortition, and lexical access in Iwaidja and Mawng. *Laboratory Phonology*, *16*(1), 1–32. https://doi.org/10.16995/labphon.15347

Bürki, A., Viebahn, M. C., Racine, I., Mabut, C., & Spinelli, E. (2018). Intrinsic advantage for canonical forms in spoken word recognition: Myth or reality? *Language, Cognition and Neuroscience, 33*(4), 494–511. https://doi.org/10.1080/23273798.2017.1388412

Capell, A., & Hinch, H. E. (1970). *Maung grammar: Texts and vocabulary* (Vol. 98). Mouton. https://doi.org/10.1515/9783111586649

Cayado, D. T., & Rastle, K. (2025, October 24). *The cost of a narrow lens: Why morphological processing and learning research needs more languages*. PsyArXiv. https://doi.org/10.31234/osf.io/edgwy_v1

Chialant, D., & Caramazza, A. (1995). Where is morphology and how is it processed? The case of written word recognition. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 55–76). Lawrence Erlbaum Associates.

Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. Harper & Row.

Clahsen, H. (1999). Lexical entries and rules of language: A multidisciplinary study of German inflection. *Behavioral and Brain Sciences*, *22*(6), 991–1060. https://doi.org/10.1017/S0140525X99002228

Collart, A. (2024). A decade of language processing research: Which place for linguistic diversity? *Glossa Psycholinguistics, 3*(1). https://doi.org/10.5070/G60111432

Cutler, A. (2008). The 34th Sir Frederick Bartlett Lecture: The abstract representations in speech processing. *Quarterly Journal of Experimental Psychology, 61*(11), 1601–1619. https://doi.org/10.1080/13803390802218542

Cutler, A., Hawkins, J. A., & Gilligan, G. (1985). The suffixing preference: A processing explanation. *Linguistics, 23*, 723–758. https://doi.org/10.1515/ling.1985.23.5.723

Evans, N. (2000). Iwaidjan, a very un-Australian language family. *Linguistic Typology*, *4*(2), 91–142.

Evans, N. (2003). *Bininj Gun-Wok: A pan-dialectal grammar of Mayali, Kunwinjku and Kune*. Pacific Linguistics, Research School of Pacific and Asian Studies, The Australian National University. https://doi.org/10.15144/PL-541

Evans, N., Fletcher, J., & Ross, B. (2008). Big words, small phrases. *Linguistics*, *46*, 89–129. https://doi.org/10.1515/LING.2008.004

Fife, J., & King, K. (1998). Celtic (Indo-European). In A. Spencer & A. M. Zwicky (Eds.), *The handbook of morphology* (pp. 477–499). Blackwell. https://doi.org/10.1002/9781405166348.ch24

Frauenfelder, U. H., & Schreuder, R. (1991). Constraining psycholinguistic models of morphological processing and representation: The role of productivity. In *Yearbook of morphology 1991* (pp. 165–183). Springer. https://doi.org/10.1007/978-94-011-2516-1_10

Gaskell, M. G., & Marslen-Wilson, W. D. (1996). Phonological variation and inference in lexical access. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(1), 144–158. https://doi.org/10.1037/0096-1523.22.1.144

Gaskell, M. G., & Marslen-Wilson, W. D. (1998). Mechanisms of phonological inference in speech perception. *Journal of Experimental Psychology: Human Perception and Performance, 24*(2), 380–396. https://doi.org/10.1037/0096-1523.24.2.380

Goldberg, A. (1995). *Constructions: A construction grammar approach to argument structure*. University of Chicago Press.

Gonnerman, L. M., Seidenberg, M. S., & Andersen, E. S. (2007). Graded semantic and phonological similarity effects in priming: Evidence for a distributed connectionist approach to morphology. *Journal of Experimental Psychology: General, 136*(2), 323–345. https://doi.org/10.1037/0096-3445.136.2.323

Gow, D. W., Jr. (2001). Assimilation and anticipation in continuous spoken word recognition. *Journal of Memory and Language, 45*(1), 133–159. https://doi.org/10.1006/jmla.2000.2764

Gow, D. W., Jr. (2002). Does English coronal place assimilation create lexical ambiguity? *Journal of Experimental Psychology: Human Perception and Performance, 28*(1), 163–179. https://doi.org/10.1037/0096-1523.28.1.163

Heath, J. (1978). *Ngandi grammar, texts, and dictionary*. Australian Institute of Aboriginal Studies.

Heath, J. (1982). *Nunggubuyu dictionary*. Australian Institute of Aboriginal Studies.

Heath, J. (1984). *Functional grammar of Nunggubuyu*. Australian Institute of Aboriginal Studies.

Jackendoff, R., & Audring, J. (2020). Relational Morphology: A cousin of construction grammar. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.02241

Kidd, E., & Garcia, R. (2022). How diverse is child language acquisition? *First Language*, *42*(6), 703–735. https://doi.org/10.1177/01427237211066405

Kilbourn-Ceron, O., Clayards, M., & Wagner, M. (2020). Predictability modulates pronunciation variants through speech planning effects: A case study on coronal stop realizations. *Laboratory Phonology*, *11*(1), 5. https://doi.org/10.5334/labphon.168

Kiparsky, P. (1971). *Historical linguistics*. In W. O. Dingwall (Ed.), *A survey of linguistic science* (pp. 576–642). University of Maryland Linguistics Program.

Kiparsky, P. (1982). Lexical morphology and phonology. In The Linguistic Society of Korea (Ed.), *Linguistics in the morning calm* (pp. 3–91). Hanshin.

Kiparsky, P. (2000). Opacity and cyclicity. *Linguistic Review 17(*2–4), 351–366. https://doi.org/10.1515/tlir.2000.17.2-4.351

Lahiri, A., & Marslen-Wilson, W. (1991). The mental representation of lexical form: A phonological approach to the recognition lexicon. *Cognition, 38*(3), 245–294. https://doi.org/10.1016/0010-0277(91)90008-R

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. MIT Press. https://doi.org/10.7551/mitpress/6393.001.0001

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*(1), 1–38. https://doi.org/10.1017/S0140525X99001776

Marslen-Wilson, W. D. (2007). Processes in language comprehension. In M. G. Gaskell (Ed.), *The Oxford handbook of psycholinguistics* (pp. 495–524). Oxford University Press.

Marslen-Wilson, W., & Warren, P. (1994). Levels of perceptual representation and process in lexical access: Words, phonemes, and features. *Psychological Review*, *101*(4), 653–675. https://doi.org/10.1037/0033-295X.101.4.653

Marslen-Wilson, W. D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive Psychology*, *10*(1), 29–63. https://doi.org/10.1016/0010-0285(78)90018-X

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, *18*(1), 1–86. https://doi.org/10.1016/0010-0285(86)90015-0

Merlan, F. (1983). *Ngalakan grammar, texts, and vocabulary* (Pacific Linguistics Series B, No. 89). Pacific Linguistics.

Norcliffe, E., Harris, A. C., & Jaeger, T. F. (2015). Introduction: Cross-linguistic psycholinguistics and its critical role in theory development: Early beginnings and recent advances. *Language, Cognition and Neuroscience, 30*(9), 1009–1032. https://doi.org/10.1080/23273798.2015.1080373

Norris, D., & McQueen, J. M. (2008). Shortlist B: A Bayesian model of continuous speech recognition. *Psychological Review*, *115*(2), 357–395. https://doi.org/10.1037/0033-295X.115.2.357

Nyhuis, P. C. (2023). *Lexical representation in Wubuy* [Doctoral dissertation, University of Melbourne]. Minerva Access. https://minerva-access.unimelb.edu.au/items/eb0592cf-56fa-4a05-b89c-c9f42499586c

Pinker, S., & Ullman, M. T. (2002). The past and future of the past tense. *Trends in Cognitive Sciences*, *6*(11), 456–463. https://doi.org/10.1016/S1364-6613(02)01990-3

Plaut, D. C. (2011). Connectionist perspectives on lexical representation. In G. Gaskell & P. Zwitserlood (Eds.), *Lexical representation: A multidisciplinary approach* (pp. 149–169). De Gruyter. https://doi.org/10.1515/9783110224931.149

Prince, A., & Smolensky, P. (1993). *Optimality Theory: Constraint interaction in generative grammar* (Technical Report No. RuCCS-TR-2). Rutgers University Center for Cognitive Science.

Ranbom, L. J., & Connine, C. M. (2007). Lexical representation of phonological variation in spoken word recognition. *Journal of Memory and Language*, *57*(2), 273–298. https://doi.org/10.1016/j.jml.2007.04.001

Rueckl, J. G., Mikolinski, M., Raveh, M., Miner, C. S., & Mars, F. (1997). Morphological priming, fragment completion, and connectionist networks. *Journal of Memory and Language*, *36*(3), 382–405. https://doi.org/10.1006/jmla.1996.2489

Rumelhart, D. E., & McClelland, J. L. (1986). On learning the past tenses of English verbs. In *Psycholinguistics: Critical concepts in psychology* (Vol. 4, pp. 216–271).

Sandefur, J. R. (1982). Kriol and the question of decreolization. *International Journal of the Sociology of Language*, *36*, 5–14. https://doi.org/10.1515/ijsl.1982.36.5

Schreuder, R., & Baayen, R. H. (1995). Modeling morphological processing. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (Vol. 2, pp. 257–294). Lawrence Erlbaum Associates.

Shaw, J. A., Carignan, C., Agostini, T. G., Mailhammer, R., Harvey, M., & Derrick, D. (2020). Phonological contrast and phonetic variation: The case of velars in Iwaidja. *Language*, *96*(3), 578–617. https://doi.org/10.1353/lan.2020.0042

Stockall, L., & Gwilliams, L. (2023). Distributed morphology and neurolinguistics. In A. Marantz, R. Rhodes, & M. Halle (Eds.), *The Cambridge handbook of distributed morphology* (pp. 385–410). Cambridge University Press. https://lingbuzz.net/lingbuzz/006928

Stump, G. T. (2001). *Inflectional morphology: A theory of paradigm structure*. Cambridge University Press. https://doi.org/10.1017/CBO9780511486333

Taft, M. (2004). Morphological decomposition and the reverse base frequency effect. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 57A*(4), 745–765. https://doi.org/10.1080/02724980343000477

Ullman, M. T. (2001). The neural basis of lexicon and grammar in first and second language: The declarative/procedural model. *Bilingualism: Language and Cognition*, *4*(2), 105–122. https://doi.org/10.1017/S1366728901000220

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition*, *92*(1–2), 231–270. https://doi.org/10.1016/j.cognition.2003.10.008

Ullman, M. T., Corkin, S., Coppola, M., Hickok, G., Growdon, J. H., Koroshetz, W. J., & Pinker, S. (1997). A neural dissociation within language: Evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. *Journal of Cognitive Neuroscience*, *9*(2), 266–276. https://doi.org/10.1162/jocn.1997.9.2.266

Ussishkin, A., Warner, N., Clayton, I., Brenner, D., Carnie, A., Hammond, M., & Fisher, M. (2017). Lexical representation and processing of word-initial morphological alternations: Scottish Gaelic mutation. *Laboratory Phonology*, *8*(1), 8. https://doi.org/10.5334/labphon.22

Van Egmond, M.-E. (2012). *Enindhilyakwa phonology, morphosyntax, and genetic position* [Doctoral dissertation, University of Sydney]. Sydney eScholarship. handle.net

Westermann, G., & Ruh, N. (2012). A neuroconstructivist model of past tense development and processing. *Psychological Review*, *119*(3), 649–677. https://doi.org/10.1037/a0028258

Zwitserlood, P. (2018). Processing and representation of morphological complexity in native language comprehension and production. In G. Booij (Ed.), *The construction of words* (pp. 583–602). Springer. https://doi.org/10.1007/978-3-319-74394-3_20