DOI: 10.26346/1120-2726-236

The role of consonant cluster features in sublexical and lexical processing of morphologically complex words

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The present study tested the postulates of Strong Morphonotactic Hypothesis (SMH; Dressler & Dziubalska-Kołaczyk 2006) and Beats-and-Binding (B&B) phonotactics model (Dziubalska-Kołaczyk 2002; 2009). According to the SMH, morphonotactic consonant clusters, which occur across morpheme boundary, are acquired earlier and processed faster and more accurately than phonotactic clusters, which occur within a morpheme. Research in several languages has corroborated this (e.g. Kamandulytė 2006; Kelić & Dressler 2019; Zydorowicz 2010). Within the B&B phonotactics model, a facilitatory role in the acquisition and processing is attributed to preferability, a concept that refers to the language-specific phonotactic preferences grounded in the acoustic features of neighbouring phonemes. While many different types of linguistic and extralinguistic information have been examined in the context of morphological processing, the interaction of acoustic and morphonotactic information has not received comparable attention. The aim of this study was to examine the role of morphonotactic and preferability features of consonant clusters in the processing of morphologically complex words in a morphologically rich language, Croatian. Two experiments were performed, an auditory sequence targeting experiment and a lexical decision task, with 71 adult Croatian L1 speakers as participants. The results indicate that the preferability of consonant clusters facilitates processing at the sublexical level, while preferability and morphonotactic information play significant facilitatory roles at the lexical level. To the best of our knowledge, this is the first study that examined both morphonotactic and preferability features at different levels of processing.

Keywords: consonant clusters, morphonotactics, preferability, morphological processing, (sub)lexical processing, Croatian.

 (received March 2024)

1. Introduction

1.1. Theoretical background

The processing of derived words has been the subject of extensive psycholinguistic and neurolinguistic research that mainly focused on determining whether derived words are processed and represented as whole forms or whether their storage and processing requires morphological decomposition. The general conclusion of the behavioural and electrophysiological studies seems to be that derived words are stored both as whole-word units and as compositional structures (Clahsen *et al.* 2003; Marslen-Wilson 2007; Taft 2004) and that they are decomposed during processing (for review see e.g. Leminen *et al.* 2019; Marslen-Wilson 2007). The question of whether decomposition occurs during the early, prelexical phase of word processing or during the later, lexico-semantic stage, has long been debated (e.g. Giraudo & Grainger 2001). Numerous studies conducted within this line of research have finally led to a consensus on the prelexical nature of morphological decomposition (e.g. Beyersmann *et al.* 2011; Longtin & Meunier 2005; Marslen-Wilson *et al.* 2008; cf. Feldman *et al.* 2015). The influence of various linguistic and psycholinguistic variables on morphological processing has been investigated, such as whole-word/stem/affix frequency, semantic transparency, affix productivity, family size, etc. (overview in Amenta & Crepaldi 2012). The interplay between orthographic and semantic information in morphological processing during visual word recognition has been studied, too (review in Rastle & Davis 2008), as has the relationship between phonological and semantic information during auditory word recognition (e.g. Bacovcin *et al.* 2017; Schwarz *et al.* 2023; for a comparison of visual and auditory modalities, see Beyersmann *et al.* 2020). However, the interplay between phonological and morphological information in the processing of morphologically complex words has not yet received comparable attention.

Morphonology is the area of interface between morphology and phonology and has its origins in the theories of Natural Morphology and Natural Phonology (Dressler 1985). Morphonotactics was also introduced as a sub-area within this concept, the one that examines consonant combinations as products of morphological operations at morpheme boundaries (Dressler & Dziubalska-Kołaczyk 2006). Morphonotactics has been under a great research focus, especially since the suggestion that the type of consonant cluster within the words of a given language may significantly influence language acquisition and processing (Dressler *et al.* 2019; Kelić *et al.* 2023; Korecky-Kröll *et al.* 2014; Zydorowicz *et al.* 2016). In the context of morphonotactics, the cluster type[1] refers to its function with respect to the information it carries. Clusters that occur at a morpheme boundary are called phonotactic clusters, and those that appear across the morpheme boundary are morphonotactic clusters. Most of the work that focuses on the investigation of the effect of cluster type on language acquisition and processing is grounded in Strong Morphonotactic Hypothesis (SMH) proposed by Dressler & Dziubalska-Kołaczyk (2006). The SMH states that the interaction of morphology and phonotactics facilitates language processing and acquisition due to the significant morphological information that the morphonotactic clusters carry, as opposed to purely phonotactic clusters.

Consonant clusters are often investigated also within other frameworks, such as the sonority framework (Parker 2017) and the Beats-and-Binding (B&B) phonotactics model established by Dziubalska-Kołaczyk (2002; 2009). As the latter model stems from the theory of Natural Phonology, and has already been used in an acquisition study testing similar assumptions in Croatian, it was our model of choice in the current study. This model accounts for the organisation of consonant clusters in a language, which depends on acoustic features of neighbouring phonemes. As it is a non-syllable model, it replaces the traditional terms for syllable components with the terms beats and non-beats. Beats are best realised by vowels and are generally more prominent, while non-beats are realised by consonants and are less prominent. Bindings connect the two in a sequence (Dziubalska-Kołaczyk *et al.* 2014). A certain combination of sounds may be more or less marked, and according to Natural Phonology, there is a strong preference for simple, unmarked phonotactic structures. This preference is determined linguistically, but also non-linguistically, i.e. it requires less cognitive effort and is easier to perceive and pronounce (Dziubalska-Kołaczyk 2002). The model lists these phonotactic preferences, which indicate the required phonological distances between cluster segments at each position within a given word of a language, measured in terms of the Net Auditory Distance (NAD; Dziubalska-Kołaczyk 2002). NAD stands for the measure of auditory distances between neighbouring phonemes in terms of the manner of articulation (MOA) and place of articulation (POA) as well as voicing, and allows the construction of the hierarchy of preferences from the most preferred to the least preferred cluster (Dziubalska-Kołaczyk 2002; see also Dressler & Kononenko-Szoszkiewicz 2021). The medial cluster is considered preferred if it conforms to the condition NAD (V1, C1) $\geq$ NAD (C1, C2) $\leq$ NAD (C2, V2). The condition reads that, for word-medial double cluster, the NAD between the two consonants should be less than between each of the consonants and its respective neighbouring beat, and it may be equal to the NAD between the first consonant and the beat preceding it. For clarification, we present the NAD calculation for the dispreferred cluster VdlV used in the current study.

MOA for /d/ = 5; MOA for /l/ = 2.5; POA for /d/ = 2.3; POA for /l/ = 2.3; for vowels MOA is 0.

To calculate NAD, the following operation has to be performed:

1. /dl/ = |(MOA1 – MOA2| + |(POA1 – POA2)| + S/O= |5 – 2.5| + |2.3 – 2.3| + 1 = 2.5 + 0 + 1= 3.5
2. NAD CC = 3.5
3. /Vd/ = |MOA1 – MOA2| = |0 – 5| = 5
4. NAD VC = 5
5. /lV/ = |MOA1 – MOA2| = |2.5 – 0| = 2.5
6. NAD CV = 2.5

Since the condition NAD (V1, C1) ≥ NAD (C1, C2) ≤ NAD (C2, V2) is not satisfied (5 ≥ 3.5 ≰ 2.5), the cluster is dispreferred.

1.2. Previous studies

Studies on consonant clusters within the SMH framework refined the hypothesis by suggesting that the earlier emergence or mastery of morphonotactic clusters in language development and the faster and more accurate processing of morphonotactic clusters is mediated by the morphological complexity of the language under study or, more specifically, by the complexity of specific morphological subsystem, e.g. inflectional morphology, derivational morphology, compound morphology (Calderone & Dressler 2021). In terms of acquisition, most studies have looked at the emergence of words with different types of clusters in language acquisition, but also at their mastery (see e.g. Calderone & Dressler 2021 for review; Kelić & Dressler 2019). There is evidence for facilitated acquisition of morphonotactic clusters in Polish (Zydorowicz 2010) and Lithuanian (Kamandulytė 2006), languages with complex morphology, but not for German with less rich inflectional morphology (Dressler *et al.* 2015). Morphonotactic precedence was also shown in a Croatian developmental study that focused on the mastery of word-initial clusters (Kelić & Dressler 2019). This study has shown that Croatian children produce morphonotactic clusters correctly earlier than homophonous phonotactic clusters. For example, morphonotactic /sp/ in *s+pustiti* 'to put down' was consistently produced correctly by the child earlier than phonotactic /sp/ in *spavati* 'to sleep', where /s/ was omitted for a longer time. This was true even when homophonous phonotactic clusters appeared first in the child's production and morphonotactic clusters emerged later. The lower lexical diversity and token frequency of morphonotactic clusters than the comparable phonotactic clusters shows that the faster development of homophonous clusters in their morphonotactic function is not due to greater frequency, i.e. more practice. Rather, it shows that morphology apparently encourages children to favour morphonotactic lemmas and to take into account the lexical change that the prefix has triggered. A subsequent study by Kelić *et al.* (2023) on the emergence of word-medial and word-final consonant clusters also partially confirmed the SMH, although considerable individual differences in the complex acquisition process were found, as well. For example, in one of the three subcorpora, i.e. in one child in particular, a clear dominance of morphonotactic clusters was observed. While Croatian word-initial consonant clusters tackled in Kelić & Dressler (2019) were formed by prefixation, word-medial clusters examined in Kelić *et al.* (2023) were also formed by a subtractive morphotactic operation leading to vowel deletion. Beside the differences between the mastery and the emergence, also different morphological processes could lead to slightly different results in the two studies. Large individual differences in the three subcorpora suggest that this hypothesis needs to be further investigated, not only in different languages, but also with respect to different morphological components and using different approaches. Generally, that study revealed interesting developmental changes in the preferability of early emerging phonotactic and morphonotactic clusters, providing insights into the mechanism of implicit learning based on subtle phonological differences in the distribution of phonemes in clusters.

In the field of language processing, the idea that SMH might be restricted to languages or morphological components with a rich morphology is best illustrated in a German study by Sommer-Lolei *et al.* (2021). The results of their two psycholinguistic experiments showed no effect of cluster type for inflection, which is relatively poor in German, a partial trend for derivation, but a positive effect for compounding which is a frequent and productive word formation pattern in all Germanic languages. To investigate processing at the lexical level, the authors used a progressive demasking task and a lexical decision task. Other studies in German focused on sublexical processing and yielded mixed results. Korecky-Kröll *et al.* (2014) reported a significant effect of morphology on processing in a visual sequence targeting experiment in which they did not distinguish between inflection, derivation and compounding. They obtained significant effects of morphology on reaction time, but not on accuracy. The presence of a morpheme boundary was found to be beneficial in a word modifying task (split-cluster task) in which participants had to reshape a morphonotactic or phonotactic cluster by adding a vowel between the consonants (Celata *et al.* 2015). This was found to be easier for clusters that occur across the morpheme boundary, especially for adolescent German speakers compared to adults. Developmental differences in sublexical processing were also evident in the second experiment of the same study, in which participants had to compare an auditorily perceived word with the letter sequences on the screen. The adolescent participants were significantly less accurate, particularly on morphonotactic items, whereas the presence of a morpheme boundary had no effect on the accuracy in adults.

The above studies aimed to investigate whether a morpheme boundary between the consonants of a cluster facilitates or impedes processing, or whether it makes no difference what type of cluster a word contains. While they took into account the postulates of SMH, they disregarded the purely phonological differences between clusters, which can be defined in terms of the auditory distances between neighbouring phonemes, i.e. preferability. This limitation has been addressed in the current study.

1.3. Croatian phonological and morphological system

Compared to other Slavic languages, Croatian is not a highly consonantal language, with the ratio of consonants to vowels defined as moderately high (Dryer & Haspelmath 2013). The majority of syllables in Croatian consist of a single consonant followed by a vowel (Škarić 1991), while the syllable structure in Croatian is typically described as moderately complex (Maddieson 2013). Consequently, consonant clusters in Croatian are also less complex than, for example, in Polish or Russian. Croatian syllables typically have one or two consonants in the onset, and one consonant in the coda (Jelaska 2004). Double consonant clusters in the onset of lexical words are much more frequent than triple consonant clusters (Kelić 2017). Both double and triple consonant clusters can be found in word-medial position.

Consonant clusters in word-initial and word-medial position can be either morphonotactic or phonotactic, with the proportion of morphonotactic clusters being higher in word-medial position than in word-initial position, which is a common feature across languages (Dressler *et al.* 2015). Unlike in other Slavic languages, consonant clusters in word-final position are rare in Croatian (Turk 1992) and are exclusively phonotactic. Unfortunately, the distribution of different types of consonant clusters in word-medial position in Croatian has not yet been comprehensively described in terms of morphonotactics.

Croatian exhibits a rather high level of morphological complexity, as do other Slavic languages. The Croatian morphological system is characterised by rich inflectional paradigms and mostly synthetically marked inflectional categories. In the nominal and adjectival paradigms, each inflectional suffix carries information about the gender of the noun, the case and number in which it is used and, in the accusative case of masculine nouns, its animacy. Pronouns are marked synthetically for person, number, gender and case. In addition, the pronominal declensions comprise numerous suppletive and homophonous forms, which makes their declension rather opaque. Verbal inflectional suffixes are marked for tense, person and number, all within a single morpheme. In some periphrastic verb constructions, e.g. perfect, conditional or passive, the gender of the subject is marked on the verbal adjective. While inflectional morphology in Croatian very rarely leads to more complex phonotactics, derivational morphology results not only in longer, but also in phonotactically more complex words.

Croatian derivational morphology represents a rich system as well, especially for verbs. Verbs can be derived from nouns (e.g. *hrana* 'food' – *hraniti* 'to feed') and adjectives (e.g. *pun* 'full' – *puniti* 'to fill'), but also from other verbs, either by prefixation or by suffixation (see, e.g., Babić 2002; Šojat *et al.* 2012). Prefixation is more productive than suffixation in the derivation of the Croatian verbs (Babić 2002). Addition of a prefix or a suffix can change the meaning of the original verb (e.g. *baciti* 'to throw' – *izbaciti* 'to throw out'), the aspect (e.g. *kupiti* 'to buy.PFV' – *kupovati* 'to buy.IPFV'), or both (e.g. *pisati* 'to write.IPFV' – *prepisati* 'to copy.PFV by writing').

In Croatian, derivation has non-trivial consequences at the phonological level. The addition of a derivational morpheme to the word stem can result in a combination of phonemes that is otherwise not frequent in a language, which might influence the efficiency of the processing of the derived word. This is captured by the term 'morphonotactics' introduced in 1.1 (*Theoretical background*), and Croatian can serve as an excellent testing ground for the predictions of the SMH. The Croatian verb derivation paradigm contains several verbal prefixes that end in a consonant (*iz-, nad-, pod-, pred-*, etc.). When a prefix that ends in a consonant is added to a verb that begins with a consonant, e.g. *is* + *puniti* 'fill.IPFV' – *ispuniti*.PFV 'to fill completely', a medial consonant cluster is formed. Depending on the articulatory features of the consonants within the newly formed cluster, the cluster is more or less preferred in the Croatian language. At the same time, the consonant cluster that results from a derivational operation is a morphonotactic cluster, as explained in 1.1 (*Theoretical background*). On the other hand, if a prefix that ends in a vowel is added to a verb that begins with a consonant cluster, e.g. *na* + *kriviti* 'slant.IPFV' – *nakriviti* 'slant.PFV', the consonant cluster in the derived verb remains phonotactic, as it was in the original verb. One and the same consonant cluster can be found in the medial position as morphonotactic or as phonotactic cluster, depending on whether the first consonant in the cluster originally belonged to the prefix or the stem (e.g. /sp/ in *is-puniti* 'to fill completely' *vs* /sp/ in *o-sporiti* 'to dispute'). According to the SMH, the processing should be facilitated in the former case due to the morphological information that the cluster carries. According to the B&B framework, the preferability of the consonant combinations within the clusters should also play a role, but this assumption had not yet been tested.

Since Croatian is a morphologically rich and complex language, studying acquisition and processing of this language may shed additional light on the postulates of SMH and B&B framework. More specifically, it may help us disentangle the exact stages of processing in such a rich system, i.e. the type of information that is relevant on different processing levels.

1.4. Present study

The aim of the present study is to examine the role of cluster type (phonotactic *vs* morphonotactic) and cluster preferability (preferred *vs* dispreferred) in sublexical and lexical processing. By addressing this aim we wish to test the postulates of SMH and B&B in Croatian, i.e. to disentangle the influence of the two cluster features on processing on different levels.

Thus, this study aims (i) to examine whether medial morphonotactic clusters are processed faster and more accurately at the level of sublexical and lexical processing than phonotactic consonant clusters, and (ii) to explore the role of preferability in processing clusters of different types, on the sublexical and lexical level. To this aim, two experiments were designed, one with auditory sequence targeting task (ASTE, Experiment 1), and another with a lexical decision task (LDT, Experiment 2).

By tackling these questions, we wish to contribute to both frameworks from two perspectives, crosslinguistic and methodological. Crosslinguistically, by investigating Croatian we hope to shed additional light on the SMH continuum and explore whether morphonotactic clusters are processed faster than phonotactic clusters in a morphologically rich system. Methodologically, by implementing experimental psycholinguistic tasks to investigate sublexical and lexical processing of words containing morphonotactic and phonotactic clusters of different preferability profiles (preferred / dispreferred) in the medial position, we plan to enrich the current approaches to this phenomenon and extend the existing corpus-based findings on their acquisition.

2. Methods

2.1. Experiment 1 (ASTE)

2.1.1. Participants

In total, 71 adults participated in Experiment 1. All were students from Croatia who acquired Croatian as their L1. None of them had a history of neurological or language disorders. Participants were recruited at two universities, University of Zagreb and University of Rijeka, and were tested as part of the experimental seminars within two obligatory courses. Prior to testing, all participants signed an informed consent, and later received course credits for participation. All individual data were de-identified and anonymised.

2.1.2. Materials

In the first step, all prefixes used in verb derivation in Croatian (Barić *et al.* 2005) were listed. For each prefix ending in a consonant, all verbs derived with this prefix were extracted from the Croatian web corpus HrWac (Ljubešić & Klubička 2016), as well as their relative frequencies. In the next step, the four-syllable verbs containing a consonant cluster across or next to the prefix-stem morpheme boundary were identified and included in the list. These verbs were then categorised according to the type of medial cluster as verbs with morphonotactic or phonotactic clusters. For some verbs the decomposition into prefix and stem does not yield a stem that is an attested lexeme in Croatian (e.g. *odbijati* 'refuse.IPFV' = *od* + **bijati vs nadjačati* 'overpower.PFV' = *nad* + *jačati*). However, this has no consequences for classifying the cluster as morphonotactic or phonotactic. For each verb the preferability of the cluster was determined using the NAD calculator which calculates net auditory distance values between consonants in the cluster in a given language and provides information on whether the cluster is preferred (Dziubalska-Kołaczyk *et al.* 2014).

Forty verbs were included in the final list of stimuli (see the complete stimulus list in the *Supplementary materials*). The number of verbs with morphonotactic *vs* phonotactic clusters in the list was equal (i.e. 20 verbs with morphonotactic clusters and 20 verbs with phonotactic clusters). Within each group 10 consonant clusters were preferred, while the remaining 10 clusters were dispreferred. In order to exclude frequency as a potential confound, the difference between relative frequencies of the verbs across different conditions was tested using the non-parametric Mann-Whitney test. No statistically significant difference was found between relative frequencies of the verbs with morphonotactic and phonotactic clusters ($W = 257$, $p = .126$), nor between relative frequencies of the verbs with preferred and dispreferred clusters ($W = 183$, $p = .655$).

Materials for the ASTE were pre-recorded audio stimuli, recorded by a native speaker of Croatian (third author) using the application for sound recording on a mobile phone. The audio files were processed in DaVinci Resolve video editor, whereby the beginning of each audio file was set to correspond to the onset of the first phoneme in a word. The experiment contained 40 items that appeared three times during the course of the experiment (twice as target stimuli, once as filler items; for details see the following section, *Procedure*).

2.1.3. Procedure

Participants were tested in two psycholinguistic laboratories in Croatia, Laboratory for Psycholinguistic Research, University of Zagreb and Laboratory for Language and Cognitive Neuroscience, University of Rijeka. The testing took place in a well-lit quiet room without distractors and was conducted using a desktop computer. Both experiments were programmed using E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA, 2016) and performed during a single session. Every participant saw the full list of stimuli in both experiments (fully crossed within-participant design), but the order of experiments was counterbalanced and the order of the stimuli within each experiment was randomised. Prior to testing, the participants read and signed the informed consent. They were allowed to take a break between the experiments. The entire session lasted from 15 to 20 minutes.

The experiment started with instructions and 6 practice items, and ended with a *Thank you* screen. Participants heard a word (a prerecorded audio stimulus) via the headphones, after which either a single consonant (the first or second consonant from the target cluster) or the entire cluster was displayed on the screen. The three versions of the task were introduced in order to minimise the monotony and learning effect in participants. Participants' task was to determine whether the auditorily presented word contained the visually presented consonant / cluster. They responded by pressing the left-most key on the CHRONOS response box for YES, and the right-most key for NO. The keys were additionally marked with green and red LED lights for YES and NO, respectively.

In two thirds of the stimuli, the visually presented consonant (a grapheme) or cluster was contained in the auditorily presented word (as a phoneme or a cluster), while in one third of the stimuli the auditorily presented word did not contain the phoneme or a cluster that were visually presented on the screen (as a grapheme or a cluster). The latter 40 stimuli were filler items and were not included in the analysis. Accuracy and reaction times (RT) were recorded in order to be compared across different conditions.

2.2. Experiment 2 (LDT)

2.2.1. Participants

The same group of students participated in Experiment 1 and Experiment 2.

2.2.2. Materials

Forty verbs used as stimuli in Experiment 1 were used in Experiment 2 as well. For the LDT it was also necessary to create pseudowords. This was done using the web-tool Wuggy (Keuleers & Brysbaert 2010). The only requirement set in the programme was that the pseudowords contained the same medial consonant clusters as their word counterparts, and that they had a form that resembled verbs in infinitive form (e.g. phonotactic cluster /dl/ in the word *predložiti* 'suggest' was also used in the pseudoword *prodlopiti*; morphonotactic cluster /zr/ in the word *razraditi* 'elaborate' was used in the pseudoword *razrebiti*). The list of stimuli consisted of 40 words and 40 pseudowords (see the complete stimulus list in the *Supplementary materials*).

2.2.3. Procedure

Experiment 2 was performed under the same conditions as Experiment 1. The experiment started with the instructions screen followed by 6 practice items, and ended with a *Thank you* screen. Participants were presented with visually displayed stimuli (words or pseudowords) on the screen and had to decide whether the presented string of graphemes is a word in Croatian. The stimuli were presented for 500 ms and participants had an additional 1500 ms of blank screen to provide the response, making the response window 2000 ms long. Participants responded using the CHRONOS response box, in the same way as in Experiment 1. Participants' accuracy and reaction times (RT) were recorded for further analyses.

3. Results

Before the analysis, normality of data distribution was assessed using the measures of skewness and kurtosis (skewness values between –2 and +2 and kurtosis values between –1 and +1 were considered to indicate a normal univariate distribution; see George & Mallery 2010). Given these criteria, in Experiment 1 the dependent variable was normally distributed in all conditions, while in Experiment 2 in some conditions standard kurtosis values were minimally exceeded. To test the influence of different factors on sublexical and lexical processing of words with different cluster features and their pseudoword counterparts, several analyses of variances with repeated measures (rmANOVAs) were performed in R (R Core Team 2021).

For the first experiment (ASTE) an ANOVA with a 2x2 factorial design was computed, with cluster type (2) and preferability (2) as factors, and reaction time as a dependent variable. In the subsequent analysis, target type was also added as a factor, as the three different versions of the task explained in the *Procedure* section may have affected participants' RTs. For the second experiment (LDT) another factor was introduced, namely lexicality,[2] resulting in a 2x2x2 factorial design, with lexicality (2), cluster type (2) and preferability (2) as factors, and reaction time as a dependent variable.

Although accuracy has been recorded, it reached ceiling for both experiments (97-98% for the first and 90-99% for the second experiment). The response accuracy in Experiment 2 was somewhat lower than in Experiment 1. These error rates are similar to the results obtained in another lexical decision task (cf. Meyer & Schvaneveldt 1971), i.e. error rates were higher for the pseudoword conditions. Due to these ceiling effects, it has been decided not to explore accuracy as a dependent variable, but rather to remove all incorrect trials from the analyses.

During the first step of the analysis one verb was found to be incorrectly coded as containing a morphonotactic cluster, and all RTs for this verb were thus excluded from the analyses in both experiments, as well as RTs for its pseudoword counterpart in Experiment 2. This resulted in an uneven distribution of verbs among different conditions, with morphonotactic dispreferred clusters represented with 9 verbs, and each of the three other cluster types represented with 10 verbs. The same was true for the pseudoword verbs in Experiment 2.

3.1. Experiment 1: ASTE

With the aim of testing the role of cluster type and preferability in language processing on the sublexical level, an auditory sequence targeting experiment was conducted. Descriptive statistics representing the mean performance of a group of native adult speakers (*N* = 71) and the distribution of the results are outlined in Table 1 and Figure 1.

CLUSTER / CONDITION	*N*	*MEAN*	*SD*
Morphonotactic dispreferred	71	558.70	103.58
Morphonotactic preferred	71	546.40	106.42
Phonotactic dispreferred	71	564.95	110.25
Phonotactic preferred	71	523.69	97.58

Table 1. Descriptive statistics for RT in each of the conditions (first experiment).

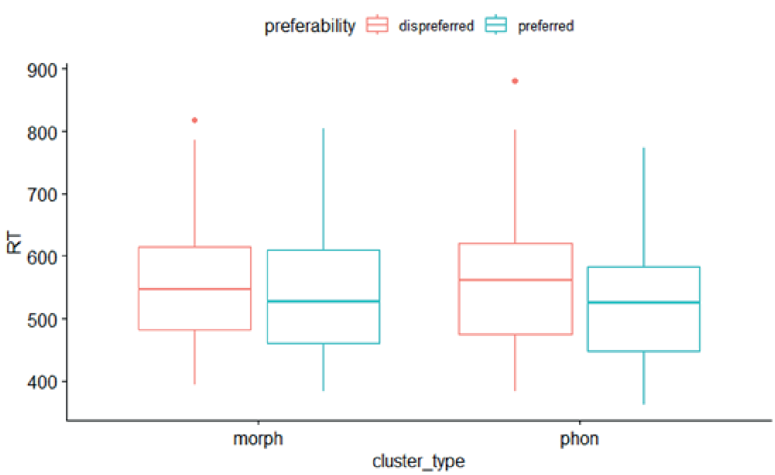

Figure 1. Distribution of RT results (first experiment; ASTE).

Table 1 and Figure 1 show that, on average, participants made the fastest choice in determining whether the visually presented consonant or a cluster is (or is not) a part of the word they previously heard when the word contained a preferred phonotactic cluster. They were the slowest when the word contained a dispreferred phonotactic cluster. Their performance was similar in the two morphonotactic conditions (preferred and dispreferred morphonotactic clusters).

Next, rmANOVA revealed the main effects of cluster type and preferability, and an interaction between cluster type and preferability (Table 2; Figure 2).

Factors	Results (rmANOVA)
Cluster type (2)	**$F(1, 70) = 7.80$; $p = 7.00e\text{-}03$**
Preferability (2)	**$F(1, 70) = 73.54$; $p = 1.59e\text{-}12$**
Cluster type x preferability	**$F(2, 69) = 27.58$; $p = 1.55e\text{-}06$**

Table 2. Main effects and an interaction obtained in Experiment 1 (significant results are highlighted for clarity).

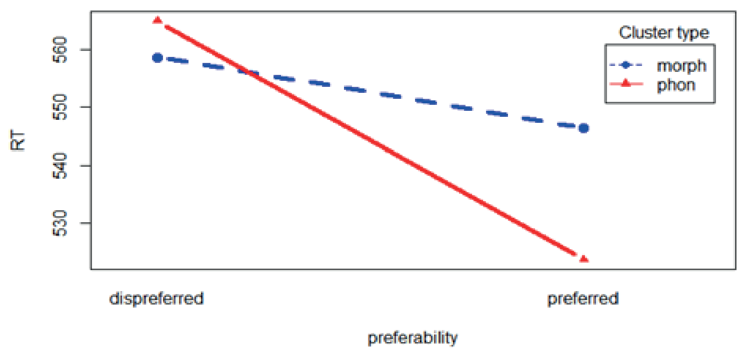

Figure 2. Interaction between cluster type and preferability (based on RT measures).

Since the three different versions of the task explained in 2.1.3 (*Procedure*) may have affected participants' RTs, we conducted one additional analysis in which we included target type as a factor. A 3x2x2 ANOVA (target type (3), cluster type (2) and preferability (2)) indeed revealed the effect of target type, F(1,70) = 96.802; *p* = 4.01e-27, while the effect of preferability, F(1,70) = 48.870; *p* = 1.30e-09, and the interaction between preferability and cluster type, F(2,69) = 27.153; *p* = 1.81e-06, remained statistically significant (Figure 3). We refer to these results in section 4 (*Discussion*).

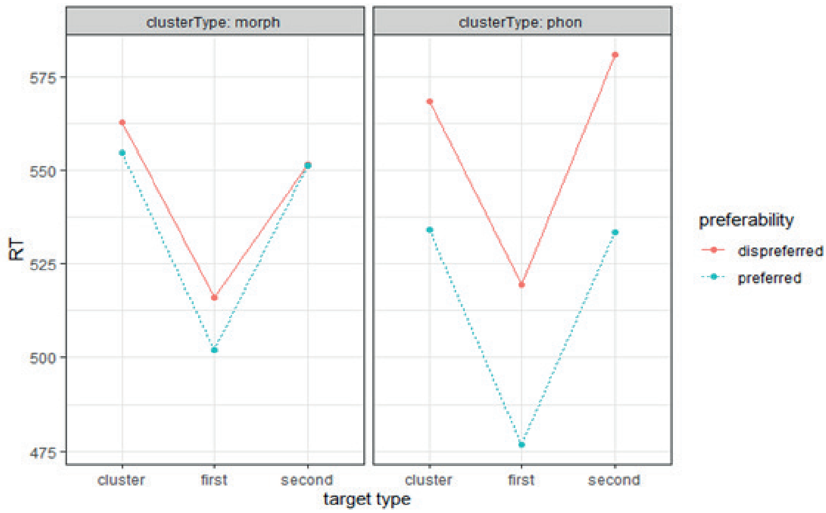

Figure 3. The effect of target type in Experiment 1 (based on RT measures).

3.2. Experiment 2: LDT

The next step was to investigate the influence of lexicality, cluster type and preferability on language processing on the lexical level. For this a lexical decision task was designed. Descriptive statistics representing the mean performance of a group of native adult speakers ($N = 71$) and the distribution of results are outlined in Table 3 and Figure 4.

LEXICALITY	CLUSTER TYPE / PREFERABILITY	*N*	*MEAN*	*SD*
Pseudoword	Morphonotactic dispreferred	71	695.62	153.32
	Morphonotactic preferred	71	689.94	137.07
Word	Morphonotactic dispreferred	71	579.00	93.79
	Morphonotactic preferred	71	559.55	95.59
Pseudoword	Phonotactic dispreferred	71	694.43	142.90
	Phonotactic preferred	71	685.83	144.54
Word	Phonotactic dispreferred	71	596.77	105.48
	Phonotactic preferred	71	590.34	103.84

Table 3. Descriptive statistics for RTs in each of the conditions (second experiment).

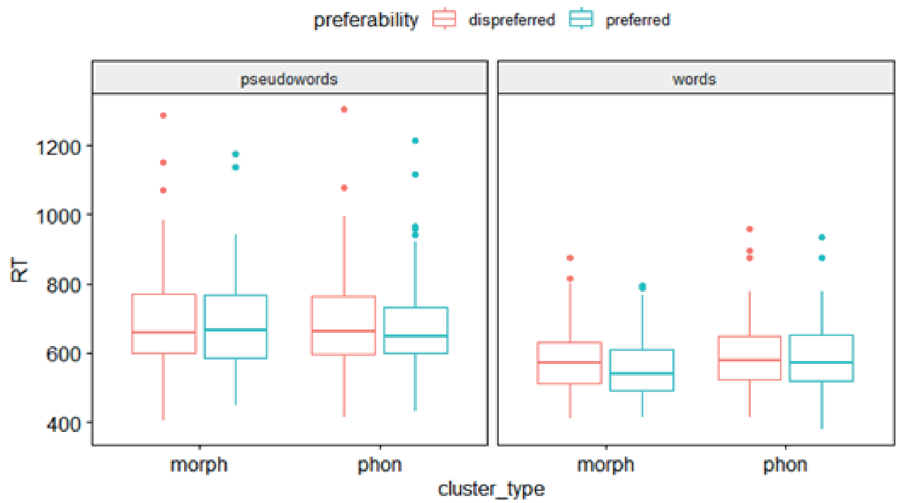

Figure 4. Distribution of RT results (second experiment; LDT).

Next, rmANOVA revealed the main effects of all three factors: lexicality, cluster type and preferability, and an interaction between lexicality and cluster type (Table 4; Figure 5).

FACTORS	RESULTS (RMANOVA)
Lexicality (2)	**$F(1, 70) = 112.80; p = 3.08e\text{-}16$**
Cluster type (2)	**$F(1, 70) = 17.88; p = 6.99e\text{-}05$**
Preferability (2)	**$F(1, 70) = 7.22; p = 9.00e\text{-}03$**
Lexicality x cluster type	**$F(2, 69) = 18.91; p = 4.57e\text{-}05$**
Lexicality x preferability	$F(2, 69) = 0.52; p = 4.72e\text{-}01$
Cluster type x preferability	$F(2, 69) = 0.50; p = 4.82e\text{-}01$
Lexicality x cluster type x preferability	$F(3, 68) = 1.41; p = 2.38e\text{-}01$

Table 4. Main effects and an interaction obtained in the second experiment (RT measure; significant results are highlighted for clarity).

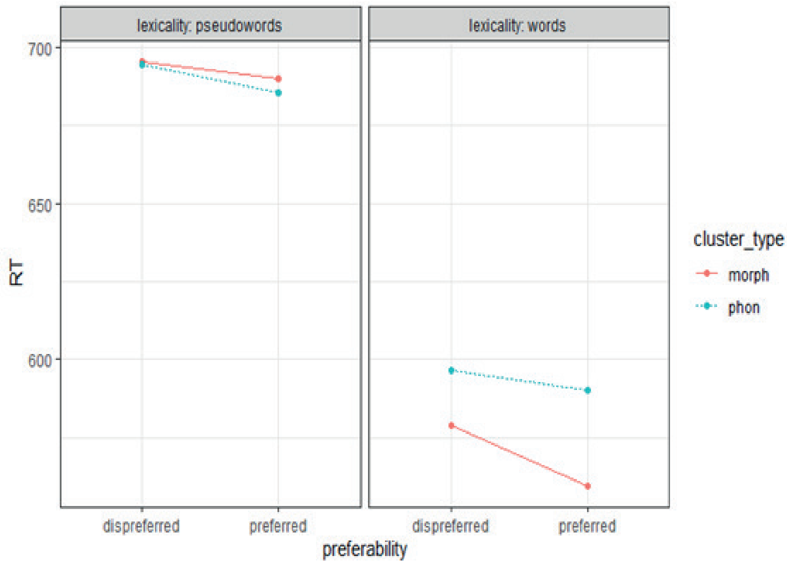

Figure 5. Interaction between lexicality and cluster type in words and pseudowords with preferred and dispreferred clusters (based on RT measures).

4. Discussion

This study, grounded in the Strong Morphonotactic Hypothesis (SMH; Dressler & Dziubalska-Kołaczyk 2006) and Beats-and-Binding (B&B) phonotactics model (Dziubalska-Kołaczyk 2002; 2009), aimed to examine how speakers of a morphologically rich language process consonant clusters of different type and preferability features on the sublexical and lexical level. To address this aim, two experiments were performed, employing different paradigms. In both experiments the accuracy reached ceiling effect, so only RTs were analysed.

In Experiment 1, the auditory sequence targeting experiment (ASTE), the main effects of cluster type and preferability were obtained. However, overall, the sublexical processing of a cluster was not facilitated by the presence of the morpheme boundary within a cluster. This finding is not in line with the studies performed within the SMH framework, in which a facilitation effect of morphonotactics was observed for the sublexical processing level (Korecky-Kröll *et al.* 2014; Giraudo *et al.* 2021). In those studies, however, the stimuli were presented visually, whereas in our Experiment 1 and in Celata *et al.* (2015) the stimuli were presented auditorily. In the latter study, no facilitation effect of morphonotactics was found at the sublexical level; on the contrary, phonotactic clusters were processed faster than morphonotactic ones by the adolescent and adult German L1 speakers. The authors proposed that the morpheme boundary within the cluster induced an inhibitory effect due to an increase in the processing cost during phonological processing (Celata *et al.* 2015: 103). However, morphological decomposition in general has been shown to have a facilitatory effect, at least at the lexical level (see e.g. Sommer-Lolei *et al.* 2021). Given that in Celata *et al.* (2015) and in the present study the modality of the stimulus presentation was auditory, we presume that this might have influenced the results. A recently performed study by Beyersmann *et al.* (2020) indeed suggests that this might be the case. The authors compared morphological processing in visual and auditory modality in two languages, German and French, and the results revealed that the morphological structure impacted processing more in the visual than in the auditory modality. The authors suggested that this might be due to a more consistent representation of morphological structure in written than in spoken language. In French, for example, morphological information included in the spelling is not available in the speech (e.g. verb forms in present tense in third person singular and third person plural are sometimes homophonous: *Elle danse.* [ɛl(ə) dɑ̃s] 'She is dancing.' / *Elles dansent.* [ɛl(ə) dɑ̃s] 'They.F are dancing.'). While this might be a valid reasoning for languages with deep orthographies, for Croatian, a language with shallow orthography and mostly one-to-one mappings between phonemes and graphemes, this seems less likely. Direct comparison of the effects of cluster type and preferability in the two modalities and processing levels remains to be performed in future studies.

The main effect of preferability observed in Experiment 1 suggests that higher preferability facilitates the processing of both morphonotactic and phonotactic clusters, which was expected at the sublexical level of processing. This hypothesis was based solely on theoretical assumptions, given that the influence of preferability on RTs for words with consonant clusters has not been previously examined. In Baroni (2014) – the only study in which the role of NAD was experimentally tested, but only via the accuracy of the consonant cluster recognition – the results demonstrated that the word-initial obstruent clusters in non-words were recognised more accurately if their NAD value was higher (Baroni 2014). To the best of our knowledge, the results of Experiment 1 are the first experimental confirmation of the facilitating effect of preferability on the speed with which consonant clusters are processed.

Furthermore, the interaction between cluster type and preferability was also significant in this experiment, in a way that preferability played a bigger role in processing phonotactic consonant clusters than in processing morphonotactic clusters, and the preferred phonotactic clusters were processed the fastest. This is not surprising since acoustic differences between consonants in preferred phonotactic clusters are smaller than those in dispreferred clusters, which makes the former easier to process. This is specific for clusters in the medial position, while the opposite is true for word-initial and word-final clusters (Dziubalska-Kołaczyk *et al.* 2014). Interestingly, a previous study on the acquisition of words containing different medial clusters in Croatian (Kelić *et al.* 2023) showed that the first emerging phonotactic clusters tended to be preferred, with their preferability decreasing over time as the vocabulary developed. On the contrary, the first emerging morphonotactic clusters tended to be dispreferred, which made them more salient. In other words, the non-preferability of consonant clusters enhanced the transparency of the morphological boundary, making it easier to be detected and acquired. Current results point to the similar pattern of processing on the sublexical level, but only with respect to the phonotactic consonant clusters. For the morphonotactic consonant clusters, the preferability feature does not play such an important role on this processing level.

The ANOVA performed with target type as a third factor reveals that the RTs differed for the three versions of the auditory sequence targeting task, as indicated in Figure 3. Overall, the participants were the fastest in recognising the first consonant, which is due to the high salience of the first element in the cluster. No difference was found regarding the speed with which the participants recognised the second consonant *vs* the cluster as a whole, which is rather interesting. If a consonant cluster is located across the morpheme boundary, the cluster is split during the morphological decomposition, as each of the consonants belongs to a different morpheme. One would argue that this might facilitate the recognition of each of the consonants, and at the same time impede the recognition of the cluster as a whole. However, the results do not support this view. It seems that the level of processing demanded by the task did not encompass a true morphological decomposition, i.e. the one that would result in splitting the cluster. Nevertheless, the morphological information did play a role, as shown by the effect of cluster type in the 2x2 ANOVA and by the interaction between cluster type and preferability. On the other hand, the morphonotactic clusters are salient as phonotactic units due to the morphological information they carry, which means that participants may have recognised the clusters faster than the individual consonants they consist of. The analysis showed that this was not the case either, because the only statistically significant difference was the one between the RTs for recognising the first consonant and the RTs for the two other variations of the task. This was found for both morphonotactic and phonotactic clusters, in which morphological decomposition undisputedly had no consequences for the cluster itself. The fact that the main effect of cluster type disappeared when target type was added as a factor, and was 'replaced' by the main effect of target type, also indicates that the pattern of RTs for the three variations of the task did not differ for morphonotactic and phonotactic clusters. The other two effects, that of preferability and the interaction between cluster type and preferability, were significant in both ANOVAs.

In the Experiment 2, a lexical decision task (LDT), the participants were faster to recognise words than pseudowords. The effect of lexicality on processing (superiority of words in comparison to non-words) is a well-known and frequently observed phenomenon (e.g. Gathercole *et al.* 2001), although a different pattern can be found in some persons with atypical language processing, depending on the type of their language-related problems (e.g. Reilly *et al.* 2012). As expected, the lexicality advantage has been obtained in the current study, too.

The main effects of cluster type and preferability were also found, in the sense that morphonotactic and preferred clusters were processed faster in the word condition. These findings are consistent with the predictions formulated within the SMH and B&B frameworks. Faster and more accurate processing of words with morphonotactic clusters has been confirmed previously for compounds in German, but not for derived words, which were shown to be processed faster than monomorphemic words regardless of whether they comprised a consonant cluster or not (Sommer-Lolei *et al.* 2021). This has led the authors to conclude that in German, due to a lower degree of morphological richness in derivation compared to compounding subsystems, the morphonotactics plays a less important role in the processing of the former than the latter. In the present study, all words contained consonant clusters and were products of derivation, which enabled us to pinpoint the role of the cluster type in the processing of derived words.

The facilitatory effect of morphonotactic compared to phonotactic clusters found in Experiment 2 provides support for the claim that the interplay between morphological and phonological information influences word processing to varying degrees, depending on the richness of the phonological and morphological systems (even subsystems) of a language (review in Calderone & Dressler 2021). Derivation is a morphologically rich subsystem in all Slavic languages; as a consequence, the number of morphonotactic clusters produced by affixation operations is higher in Slavic than in Germanic languages (Dressler *et al.* 2019). The comparison of the results from Sommer-Lolei *et al.* (2021) and from the current study indicates that this distributional property is parallelled by the differences in processing mechanisms. The language-specific nature of the processing of derivational morphology was explicitly tested outside the SMH framework, as well. For example, the aforementioned Beyersmann *et al.*'s (2020) study demonstrated that the efficiency with which the participants processed morphologically complex words depended on the productivity of the morphological subsystem that was considered most relevant for processing the stimuli in a given language. This was reflected in a higher efficiency of stem extraction in the speakers of a language with greater morphological richness in the subsystem of compounding, i.e. German.

The results of the Experiment 2 represent the first experimental confirmation of the facilitatory role of morphonotactic status of consonant clusters in word processing in Croatian. The same is true for the role of cluster preferability. The processing of derived verbs containing medial consonant clusters was faster when the cluster was preferred, which emphasises the role of phonotactic information in word processing. The speed with which speakers process different consonant combinations depends on the preferability of these combinations in their language. This naturally affects the processing speed of the word as a whole, as the results of both experiments show. As subtle as the differences in the NAD may seem, the speakers are clearly sensitive to them in their word processing, regardless of whether the word is processed only at the sublexical or at the lexical level, too.

The preferability of consonant clusters had a facilitating effect in both lexicality conditions, indicating that the effect is not limited to real words. This pattern of results was expected given the facilitatory effect of preferability observed in Experiment 1, and provides further support for the claim that the specific type of acoustic and phonological information, subsumed under the notion of cluster preferability, influenced the ease with which a consonant cluster, and subsequently, a word/pseudoword that contains the cluster, was processed. Moreover, it shows that the preferability affects the processing in both auditory and visual modality, which represents a novel insight. Based on these findings, a stronger effect of preferability might have been expected for pseudowords than for real words, since the decoding of the former relies more strongly on the phonological processing. However, our results do not seem to support this hypothesis. Whether this is due to a high transparency of the Croatian orthography, which facilitates the reading of pseudowords in general, or to some other factor, remains to be examined in the future.

The most important finding that clearly corroborates SMH in Croatian is the significant interaction between lexicality and cluster type, which points to the fact that healthy adult speakers of Croatian process derived verbs faster when they contain morphonotactic consonant clusters. Being sensitive to the phonotactic patterns of their language, speakers know that an infrequent combination of phonemes is unlikely to occur within a linguistic unit, i.e. a word stem or a morpheme. The consonant clusters are therefore quickly interpreted as probable places of juncture of different linguistic units. This accelerates the recognition of morpheme boundaries and consequently the morphological decomposition, a mandatory stage in the processing of morphologically complex words (McCormick *et al.* 2009). In contrast, when a consonant cluster is positioned next to a morpheme boundary, morphological decomposition does not occur as quickly because there are no phonotactic cues that could facilitate the identification of the morpheme boundary. In this case, the speed of processing of a consonant cluster depends solely on its preferability, as the results of the two experiments in the present study show.

The same pattern was not found for the pseudoword condition (Figure 5). Previous research has shown that morphologically complex pseudowords are morphologically decomposed during processing, just like real morphologically complex words, thus supporting the view of morphological decomposition as an early, prelexical process (review in Amenta & Crepaldi 2012). This was evidenced by longer RTs for pseudowords with real derivation affixes than for pseudowords with non-existent affixes (Burani *et al.* 1997; Crepaldi *et al.* 2010). It has also been found that pseudowords with higher frequency affixes are processed more slowly than pseudowords with lower frequency affixes (e.g. Burani & Thornton 2003). Morphological decomposition in pseudowords triggers a futile search of the mental lexicon, which is ultimately unsuccessful as it cannot result in successful lexical access and retrieval. Importantly, the search seems to be more persistent when the affixes are real, more frequent or more salient, which translates into longer RTs. In a way, these pseudowords are more wordlike than the ones with non-existent, low-frequency or low-salience affixes, which is why a longer time is needed for them to be rejected as possible real words. In the present study, all pseudowords are morphologically complex and thus decomposed during the processing; however, this process cannot rely on the morphonotactic information as the morphonotactic or the phonotactic feature of these clusters is arbitrary, i.e. inherited from their real word counterparts. Since the present study is the only study grounded in SMH in which the RTs for pseudowords are reported, a comparison with the results of other studies is not possible. Interestingly, the results obtained for the pseudowords follow the pattern observed for sublexical processing in Experiment 1, in that the presence of a morphonotactic cluster fails to facilitate the processing, or even hinders it, while preferability exhibits (moderately) facilitating effect. This is in line with the prelexical nature of processing triggered by both ASTE and pseudoword processing.

The results of the two experiments conducted in the present study suggest that the extent to which preferability and cluster type each influence processing may depend on the experimental paradigm, i.e. on the depth of processing required by the task. When the task did not require full lexical access, as in the first experiment (ASTE), the RTs were the shortest for the verbs with preferred phonotactic clusters. In the second experiment (LDT), on the other hand, participants were the fastest to recognise verbs with the preferred morphonotactic clusters.

The results of the present study fit nicely with the results from previous studies on the roles of cluster type and preferability in acquisition in Croatian, and an analogy can be put forward between the two L1 acquisition stages and the two processing stages. Interestingly, similar to the first L1 acquisition stage, preferability, and not so much the morphological boundary, facilitates sublexical processing. At the stage where word meaning is not required or available due to the limited, undeveloped vocabulary at the earliest stage of language development (Kelić *et al.* 2023), listeners rely on the predicted distributions, unmarked and intuitively plausible. As Natural Phonology and Natural Morphology (Dressler 1985) emphasise, the rare and deviant language input must be motivated, so the first dispreferred clusters in child language are morphonotactic, making them more salient and facilitating morphological development. These less preferred morphonotactic clusters become a cue for characterising a sound sequence in the input as a word in the next stage of lexical development. This precedence of morphonotactics, once established, persists and influences word processing. In adults with a functional and interconnected mental lexicon, the interaction of lexicality and cluster type, but not preferability, shows that full lexical access is greatly facilitated by the morphological boundary.

5. Contributions and limitations

The current study sheds light on the way different consonant clusters are processed in a morphologically rich language, and thus has important cross-linguistic and theoretical implications with regard to the recent postulates of the SMH. The contributions are also methodological, as different experimental psycholinguistic tasks were implemented to investigate sublexical and lexical processing by controlling and manipulating different features of the clusters. Finally, in this study we decided to include the preferability component in addition to the cluster type, in order to extend the existing findings on cluster features that affect processing on each level in different languages. To the best of our knowledge, this is the first study that examined not only the morphonotactic features of consonant clusters, but also their preferability and how both affect processing at different levels. This is also the first study that experimentally tested and confirmed the effect of preferability on word processing, and in both modalities.

Despite the gained insights, the study has some limitations that should be addressed in the future. They mainly relate to a relatively small sample size, which consisted exclusively of university students. In addition, the stimuli were isolated words and not a connected text, which does not reflect real-life language processing. In the future, the same phenomena should be investigated at the sentence and above sentence level, possibly using also some other methods. Finally, as the results of some previous studies suggest (e.g. Celata *et al.* 2015; Marshall & Van der Lely 2007; Marshall *et al.* 2010), it would be interesting to include typically developing children and children with developmental language disorder in the study, to test whether the same advantage in processing morphological information can be found in younger L1 Croatian speakers, especially those with profound difficulties in processing phonological and morphological information.

6. Conclusions

The two experiments conducted in this study confirm the Strong Morphonotactic Hypothesis (SMH; Dressler & Dziubalska-Kołaczyk 2006) showing a powerful interplay between phonotactics and morphology, where different information is used at different stages of word processing. Focusing on verbal derivational morphology in a morphologically rich language, Croatian, ensured phonotactic complexity as a consequence of morphological operations and thus provided a suitable context for testing the SMH.

In this study, in addition to the SMH, we addressed another theoretical framework, Beats and Binding phonotactics model (B&B; Dziubalska-Kołaczyk 2002; 2009), and the combination of the two led to interesting results. While morphological decomposition already takes place at the level of sublexical processing as the first step towards word meaning, at this stage the preferability of consonant clusters is the main facilitator of processing. However, in the next processing stage, at the lexical level, morphonotactic information starts to play a significant facilitatory role.

7. Supplementary materials

S1. Stimulus list – first experiment

STIMULUS	MORPHOLOGICAL DECOMPOSITION (PREFIX + STEM)	TRANSLATION	CONSONANT / CLUSTER ON THE SCREEN	CLUSTER VxxV	CLUSTER TYPE	CLUSTER PREFERABILITY
odbijati	od-bijati	refuse.IPFV	D	db	morph	pref
odbaciti	od-baciti	dismiss.PFV	D	db	morph	pref
izgubiti	iz-gubiti	lose.PFV	Z	zg	morph	pref
istaknuti	is-taknuti	highlight.PFV	S	st	morph	pref
rastopiti	ras-topiti	melt.PFV	S	st	morph	pref
optužiti	op-tužiti	accuse.PFV	T	pt	morph	pref
odgajati	od-gajati	raise.IPFV	G	dg	morph	pref
ispuniti	is-puniti	fulfil.PFV	P	sp	morph	pref
otkazati	ot-kazati	cancel.PFV	K	tk	morph	pref
raskinuti	ras-kinuti	break_up.PFV	K	sk	morph	pref
odlučiti	od-lučiti	decide.PFV	D	dl	morph	dispref
nadjačati	nad-jačati	overpower.PFV	D	dj	morph	dispref
predložiti	pred-ložiti	suggest.PFV	D	dl	morph	dispref
usvojiti[3]	u-svojiti	adopt.PFV	S	sv	*morph	dispref
razlučiti	raz-lučiti	discern.PFV	Z	zl	morph	dispref
razmisliti	raz-misliti	think_about.PFV	M	zm	morph	dispref
obvezati	ob-vezati	oblige.PFV	V	bv	morph	dispref
razraditi	raz-raditi	elaborate.PFV	R	zr	morph	dispref

razvijati	raz-vijati	develop.IPFV	V	zv	morph	dispref
odnositi	od-nositi	refer.PFV	N	dn	morph	dispref
postajati	po-stajati	become.IPFV	S	st	phon	pref
ustupiti	u-stupiti	give_way.PFV	S	st	phon	pref
usporiti	u-sporiti	slow_down.PFV	S	sp	phon	pref
uspavati	u-spavati	put_to_sleep.PFV	S	sp	phon	pref
opsovati	o-psovati	curse.PFV	P	ps	phon	pref
postidjeti	po-stidjeti	shame.PFV	T	st	phon	pref
uskočiti	u-skočiti	jump_into.PFV	K	sk	phon	pref
postaviti	po-staviti	set.PFV	T	st	phon	pref
postupati	po-stupati	act.IPFV	T	st	phon	pref
uspijevati	u-spijevati	succeed.IPFV	P	sp	phon	pref
otvoriti	o-tvoriti	open.PFV	T	tv	phon	dispref
obratiti	o-bratiti	address.PFV	B	br	phon	dispref
pretvoriti	pre-tvoriti	convert.PFV	T	tv	phon	dispref
zaključati	za-ključati	lock_up.PFV	K	klj	phon	dispref
usrećiti	u-srećiti	make_happy.PFV	S	sr	phon	dispref
nakriviti	na-kriviti	slant.PFV	R	kr	phon	dispref
oprostiti	o-prostiti	forgive.PFV	R	pr	phon	dispref
obrijati	o-brijati	shave.PFV	R	br	phon	dispref

zakvačiti	za-kvačiti	pin.PFV	V	kv	phon	dispref
zaklopiti	za-klopiti	close.PFV	L	kl	phon	dispref
odbijati	od-bijati	refuse.IPFV	DB	db	morph	pref
odbaciti	od-baciti	dismiss.PFV	DB	db	morph	pref
izgubiti	iz-gubiti	lose.PFV	ZG	zg	morph	pref
istaknuti	is-taknuti	highlight.PFV	ST	st	morph	pref
rastopiti	ras-topiti	melt.PFV	ST	st	morph	pref
optužiti	op-tužiti	accuse.PFV	PT	pt	morph	pref
odgajati	od-gajati	raise.IPFV	DG	dg	morph	pref
ispuniti	is-puniti	fulfil.PFV	SP	sp	morph	pref
otkazati	ot-kazati	cancel.PFV	TK	tk	morph	pref
raskinuti	ras-kinuti	break_up.PFV	SK	sk	morph	pref
odlučiti	od-lučiti	decide.PFV	DL	dl	morph	dispref
nadjačati	nad-jačati	overpower.PFV	DJ	dj	morph	dispref
predložiti	pred-ložiti	suggest.PFV	DL	dl	morph	dispref
usvojiti	u-svojiti	adopt.PFV	SV	sv	*morph	dispref
razlučiti	raz-lučiti	discern.PFV	ZL	zl	morph	dispref
razmisliti	raz-misliti	think_about.PFV	ZM	zm	morph	dispref
obvezati	ob-vezati	oblige.PFV	BV	bv	morph	dispref
razraditi	raz-raditi	elaborate.PFV	ZR	zr	morph	dispref
razvijati	raz-vijati	develop.IPFV	ZV	zv	morph	dispref

odnositi	od-nositi	refer.PFV	DN	dn	morph	dispref
postajati	po-stajati	become.IPFV	ST	st	phon	pref
ustupiti	u-stupiti	give_way.PFV	ST	st	phon	pref
usporiti	u-sporiti	slow_down.PFV	SP	sp	phon	pref
uspavati	u-spavati	put_to_sleep.PFV	SP	sp	phon	pref
opsovati	o-psovati	curse.PFV	PS	ps	phon	pref
postidjeti	po-stidjeti	shame.PFV	ST	st	phon	pref
uskočiti	u-skočiti	jump_into.PFV	SK	sk	phon	pref
postaviti	po-staviti	set.PFV	ST	st	phon	pref
postupati	po-stupati	act.IPFV	ST	st	phon	pref
uspijevati	u-spijevati	succeed.IPFV	SP	sp	phon	pref
otvoriti	o-tvoriti	open.PFV	TV	tv	phon	dispref
obratiti	o-bratiti	address.PFV	BR	br	phon	dispref
pretvoriti	pre-tvoriti	convert.PFV	TV	tv	phon	dispref
zaključati	za-ključati	lock_up.PFV	KLJ	klj	phon	dispref
usrećiti	u-srećiti	make_happy.PFV	SR	sr	phon	dispref
nakriviti	na-kriviti	slant.PFV	KR	kr	phon	dispref
oprostiti	o-prostiti	forgive.PFV	PR	pr	phon	dispref
obrijati	o-brijati	shave.PFV	BR	br	phon	dispref
zakvačiti	za-kvačiti	pin.PFV	KV	kv	phon	dispref

zaklopiti	za-klopiti	close.PFV	KL	kl	phon	dispref
odbijati	od-bijati	refuse.IPFV	P	db	morph	pref
odbaciti	od-baciti	dismiss.PFV	V	db	morph	pref
izgubiti	iz-gubiti	lose.PFV	SR	zg	morph	pref
istaknuti	is-taknuti	highlight.PFV	ZD	st	morph	pref
rastopiti	ras-topiti	melt.PFV	ŠP	st	morph	pref
optužiti	op-tužiti	accuse.PFV	B	pt	morph	pref
odgajati	od-gajati	raise.IPFV	K	dg	morph	pref
ispuniti	is-puniti	fulfil.PFV	ŠK	sp	morph	pref
otkazati	ot-kazati	cancel.PFV	DB	tk	morph	pref
raskinuti	ras-kinuti	break_up.PFV	ŠT	sk	morph	pref
odlučiti	od-lučiti	decide.PFV	P	dl	morph	dispref
nadjačati	nad-jačati	overpower.PFV	V	dj	morph	dispref
predložiti	pred-ložiti	suggest.PFV	TV	dl	morph	dispref
usvojiti	u-svojiti	adopt.PFV	ZL	sv	*morph	dispref
razlučiti	raz-lučiti	discern.PFV	SV	zl	morph	dispref
razmisliti	raz-misliti	think_about.PFV	V	zm	morph	dispref
obvezati	ob-vezati	oblige.PFV	F	bv	morph	dispref
razraditi	raz-raditi	elaborate.PFV	SL	zr	morph	dispref
razvijati	raz-vijati	develop.IPFV	ŠT	zv	morph	dispref

odnositi	od-nositi	refer.PFV	BL	dn	morph	dispref
postajati	po-stajati	become.IPFV	Z	st	phon	pref
ustupiti	u-stupiti	give_way.PFV	D	st	phon	pref
usporiti	u-sporiti	slow_down.PFV	ŠK	sp	phon	pref
uspavati	u-spavati	put_to_sleep.PFV	CK	sp	phon	pref
opsovati	o-psovati	curse.PFV	BL	ps	phon	pref
postidjeti	po-stidjeti	shame.PFV	C	st	phon	pref
uskočiti	u-skočiti	jump_into.PFV	G	sk	phon	pref
postaviti	po-staviti	set.PFV	GL	st	phon	pref
postupati	po-stupati	act.IPFV	DV	st	phon	pref
uspijevati	u-spijevati	succeed.IPFV	ČK	sp	phon	pref
otvoriti	o-tvoriti	open.PFV	K	tv	phon	dispref
obratiti	o-bratiti	address.PFV	L	br	phon	dispref
pretvoriti	pre-tvoriti	convert.PFV	FT	tv	phon	dispref
zaključati	za-ključati	lock_up.PFV	PL	klj	phon	dispref
usrećiti	u-srećiti	make_happy.PFV	ZD	sr	phon	dispref
nakriviti	na-kriviti	slant.PFV	L	kr	phon	dispref
oprostiti	o-prostiti	forgive.PFV	B	pr	phon	dispref
obrijati	o-brijati	shave.PFV	DV	br	phon	dispref
zakvačiti	za-kvačiti	pin.PFV	GR	kv	phon	dispref
zaklopiti	za-klopiti	close.PFV	GL	kl	phon	dispref

S2. Stimulus list – second experiment

WORD	MORPHOLOGICAL DECOMPOSITION (PREFIX + STEM)	TRANSLATION	PSEUDOWORD	CLUSTERVXXV	CLUSTER TYPE	CLUSTER PREFERABILITY
odbijati	od-bijati	refuse.IPFV	odbinati	db	morph	pref
odbaciti	od-baciti	dismiss.PFV	odbapati	db	morph	pref
izgubiti	iz-gubiti	lose.PFV	izgužiti	zg	morph	pref
istaknuti	is-taknuti	highlight.PFV	istašluti	st	morph	pref
rastopiti	ras-topiti	melt.PFV	rastošiti	st	morph	pref
optužiti	op-tužiti	accuse.PFV	uptumiti	pt	morph	pref
odgajati	od-gajati	raise.IPFV	odgapati	dg	morph	pref
ispuniti	is-puniti	fulfil.PFV	aspuliti	sp	morph	pref
otkazati	ot-kazati	cancel.PFV	itkanati	tk	morph	pref
raskinuti	ras-kinuti	break_up.PFV	raskoniti	sk	morph	pref
odlučiti	od-lučiti	decide.PFV	odluniti	dl	morph	dispref
nadjačati	nad-jačati	overpower.PFV	nadjesiti	dj	morph	dispref
predložiti	pred-ložiti	suggest.PFV	prodlopiti	dl	morph	dispref
usvojiti	u-svojiti	adopt.PFV	usvumiti	sv	*morph	dispref
razlučiti	raz-lučiti	discern.PFV	nazlumiti	zl	morph	dispref
razmisliti	raz-misliti	think_about.PFV	razmoditi	zm	morph	dispref
obvezati	ob-vezati	oblige.PFV	obvamati	bv	morph	dispref
razraditi	raz-raditi	elaborate.PFV	razrebiti	zr	morph	dispref
razvijati	raz-vijati	develop.IPFV	razvepati	zv	morph	dispref

odnositi	od-nositi	refer.PFV	odnežiti	dn	morph	dispref
postajati	po-stajati	become.IPFV	postadati	st	phon	pref
ustupiti	u-stupiti	give_way.PFV	istumiti	st	phon	pref
usporiti	u-sporiti	slow_down.PFV	isporati	sp	phon	pref
uspavati	u-spavati	put_to_sleep.PFV	uspolati	sp	phon	pref
opsovati	o-psovati	curse.PFV	upsinati	ps	phon	pref
postidjeti	po-stidjeti	shame.PFV	postebleti	st	phon	pref
uskočiti	u-skočiti	jump_into.PFV	uskubiti	sk	phon	pref
postaviti	po-staviti	set.PFV	pustamiti	st	phon	pref
postupati	po-stupati	act.IPFV	postekati	st	phon	pref
uspijevati	u-spijevati	succeed.IPFV	ospijeriti	sp	phon	pref
otvoriti	o-tvoriti	open.PFV	utvesiti	tv	phon	dispref
obratiti	o-bratiti	address.PFV	obruditi	br	phon	dispref
pretvoriti	pre-tvoriti	convert.PFV	protvokati	tv	phon	dispref
zaključati	za-ključati	lock_up.PFV	zakljarati	klj	phon	dispref
usrećiti	u-srećiti	make_happy.PFV	usrođiti	sr	phon	dispref
nakriviti	na-kriviti	slant.PFV	nakrumiti	kr	phon	dispref
oprostiti	o-prostiti	forgive.PFV	uprožljati	pr	phon	dispref
obrijati	o-brijati	shave.PFV	obromiti	br	phon	dispref
zakvačiti	za-kvačiti	pin.PFV	zakvediti	kv	phon	dispref
zaklopiti	za-klopiti	close.PFV	zaklažiti	kl	phon	dispref

Abbreviations

ASTE = Auditory Sequence Targeting Experiment; B&B = Beats-and-Binding; C = consonant; dispref = dispreferred cluster; F = feminine; HrWac = Croatian Web Corpus; IPFV = imperfective; LDT = Lexical Decision Task; MOA = Manner of Articulation; morph = morphonotactic cluster; NAD = Net Auditory Distance; PFV = perfective; phon = phonotactic cluster; POA = Place of Articulation; pref = preferred cluster; RT = Reaction Time; SMH = Strong Morphonotactic Hypothesis; V = vowel.

Acknowledgements

This study was conducted within the *Bilateral project IPCH-2022-04-3316 'Measurement reliability of individual differences in sentence processing: A cross-linguistic perspective (MeRID)'*, funded by the Croatian science foundation and Swiss national science foundation, and the international project *'Crosslinguistic project on pre- and protomorphology in language acquisition'* (PI professor Wolfgang U. Dressler, University of Vienna, Austrian Academy of Sciences). It was funded by the project *'Research on the prerequisites for the development of an automated screening of the reading skills of third and fourth graders* (uniri-iskusni-drustv-23-91)'.

Competing interests

None to declare.

Notes

1 In phonotactic and corpus-based research, the term 'cluster type' is typically used with reference to a consonant sequence with a unique phonological composition, and stands in contrast to tokens (repetitions, occurrences in a given corpus or resource). Throughout this paper the term 'cluster type' is reserved for the distinction of phonotactic as opposed to morphonotactic sequences, and not for the traditional understanding of the term.

2 Lexicality (superiority of processing words in comparison to non-words) is a well-known and frequently observed phenomenon in psycholinguistic studies (e.g. Gathercole *et al.* 2001), usually tested with a lexical decision task in which a person has to decide whether a stimulus (presented visually or auditorily) is or is not a real word.

3 The verb *usvojiti* 'adopt' was initially erroneously classified as a verb with morphonotactic cluster, whereas in fact it contains a phonotactic cluster (*u-svojiti*). The verb and its pseudoword counterpart were therefore removed from the analysis.

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