Phonotactic processing and morpheme boundaries: word-final /Cst/ clusters in German

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Two experiments showed that, when processing consonant clusters of their native language, the speakers are sensitive to the presence of a morphemic boundary at some point of the cluster. In the first experiment, words with tri-consonantal final cluster had to be produced by inserting an /i/ in the cluster; the clusters containing a morpheme boundary were more frequently split according to the position of the boundary while the corresponding clusters included in a mono-morphemic word were split according to different options. In the second experiment, the subjects had to detect tri-consonantal clusters while a series of German words was auditorily presented; clusters included in monomorphemic words were easier to detect than homophonous clusters which spanned a morpheme boundary. The impact of morphonotactics on cluster processing was stronger on adolescents than on adults in Experiment 1. The results thus indicated that in offline and online processing of phonotactic structures, morphological information can be available and impact on the recognition and manipulation of clusters.

1. Introduction

Language-specific phonotactic patterns are known to affect multiple aspects of language processing, from segmentation of the speech stream (e.g. Saffran *et al.* 1996) to word learning (e.g. Storkel 2001), from phonological acquisition (e.g. Freedman & Barlow 2012) to morphological decomposition (e.g. Hay 2003). Phonotactics is exploited to locate word boundaries (e.g. McQueen 1998), but the speakers are also sensitive to differences between inter- and intra-word phonotactics (Mattys *et al.* 1999, Hay 2003). For example, words like *inhumane* in English are more likely to be decomposed than words like *insincere*, because the /nh/ transition across the morpheme boundary is not found word-internally in that language, while the /ns/ transition is well attested (e.g. *fancy*, *tinsel*) (Hay 2003: 16). Phonotactics is therefore also exploited to locate morpheme boundaries.

The phonotactics of morpheme concatenation is referred to as morphonotactics by Dressler & Dziubalska-Kołaczyk (2006), Dressler *et al.* (2010). Some studies observed that sequences occurring only or by default across a morpheme boundary (thus being

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prototypical morphonotactic sequences) are acquired earlier and faster than lexical (or purely phonotactic) clusters by typically developing children in Lithuanian (Kamandulyte 2006) and Polish (Zydorowicz 2010); English children with grammatical-specific SLI perform better in regular past tense verbs when verbs contain clusters that are intra-morphemically legal than when they contain clusters that are only cross-morphemically legal (Marshall & van der Lely 2006). Consequently, it is claimed that morphology helps phonological acquisition: due to the interplay of phonotactics with morphotactics, morphonotactic sequences facilitate morphological and lexical acquisition. A facilitatory effect of morphological boundaries on phonological acquisition is attested in the recent literature also for word-final consonants in English: word-final sibilant fricatives are longer in plurals (such as *toes)* compared to monomorphemic words (such as *nose*) in adult speech, and children from 2 years of age onwards appear to be able to exploit such cues in fricative acquisition and to correctly reproduce the adult speech pattern (Song *et al.* 2013; see also Plag *et al.* 2015 for further evidence of morpho-phonetic effects in the realization of morphemic and non-morphemic word-final /s/ in a conversational English corpus). However, Freiberger (2014) investigated the early spontaneous speech data of three children acquiring Austrian German and did not find an advantage of morphonotactic over phonotactic clusters. Likewise, Korecky-Kröll & Dressler (submitted) investigated 3-year old children's spontaneous production of German consonant clusters and found no difference between morphonotactic and phonotactic clusters (although with different results according to the children's socio-economic status). Results on acquisition are thus less clear for German than for the other languages investigated.

Moreover, according to the Strong Morphonotactic Hypothesis, phonotactics is assumed to help morphological decomposition in adult processing too: if a certain sequence occurs only or by default over a morpheme boundary, it should be processed faster and more accurately than a comparable ordinary phonotactic sequence (Korecky-Kröll *et al.* 2014). In an experiment on German, visual targets corresponding to one phoneme (i.e., /t/) or two-phoneme sequences (i.e., /st/, /an/) were detected faster when separated from the word stem by a morphological boundary (e.g. *lobst* 'you praise', 2nd sg. present (*lob+st*); *bravste* 'bravest', superlative (*brav+ste*)) than when they were part of the word stem (e.g. *Obst* 'fruit'; *Bürste* 'brush'). This result was interpreted as a supportive effect of morphology on the speed with which individual phonemes or two-phoneme phonotactic sequences are processed.

If, however, morphology impacts the processing of clusters, then its effects should be visible also in the case of those sequences that straddle a morphological boundary. In particular, we may expect different processing for pairs of homophonous phonotactic sequences that may or may not occur across a morpheme boundary in the lexicon. These are called non-exclusively morphonotactic sequences in Dressler & Dziubalska-Kołaczyk (2006). For example, word-final /nst/ in German may appear in monomorphemic words (e.g. *Wanst*, 'paunch') as well as in the concatenation of the 2nd sg. verbal morpheme in /n/-final roots (e.g. *kannst*, '(you) can'). In this paper, clusters such as /nst/ in *Wanst* will be referred to as phonotactic clusters and clusters such as /nst/ in *kannst* as morphonotactic clusters.

Non-exclusively morphonotactic clusters can be preferentially phonotactic or morphonotactic, according to a gradual scale of preferences. The preference of a cluster to appear as phonotactic or morphonotactic in a language may be measured in terms of number of items in the lexicon (word types) or of the cumulated frequency of all lexical items in a corpus (number of tokens).

In a computational study of German (mor)phonotactic clusters (Calderone *et al.* 2014), a corpus-based model of neural network activation trained on a German corpus was used to ascertain if word-final German morphonotactic clusters produced a different representation from their purely phonotactic counterparts. The computational model, called PHACTS (Calderone & Celata 2012, Celata *et al.* 2011), simulated the formation of phonotactic knowledge in the mind of a German speaker who was exposed to a stream of phonological words by gradually developing a knowledge representation of the statistical regularities that shape the phonotactics of that language. Starting from the statistical knowledge that were deducible from the German CELEX database (Baayen *et al.* 1995), the model generated activation-based representations of full lexical forms and, crucially for our purposes, of the clusters included in those specific lexical forms. Experimental clusters were the non-exclusively morphonotactic sequence /nst/ and the exclusively morphonotactic sequences /mst/ and /xst/. The results showed that within-group variability in the activation value for the /nst/ clusters turned out to be significantly higher than for both /mst/ and /xst/ clusters. The results were interpreted as evidence in support of different phonotactic representations for the morphonotactic compared to the phonotactic /nst/ clusters. Additionally, the study suggested that the representation of morphonotactic clusters could emerge from corpus information about the phonotactics of the language (including the co-occurrence of the clusters with specific vowels and consonant-vowel sequences, the relative frequency of vowel-consonant chunks and of phonological neighbors).

Do the speakers implicitly exploit such "proliferation of representations and extensive cross-activation" (Libben 2010: 12) when processing the consonantal clusters of mono- and bimorphemic words?

The present study aims at answering this question by testing the German speakers' productive and perceptive reactions to tri-consonantal clusters with different (mor)phonotactic status. It therefore represents a psycholinguistic continuation of Calderone *et al.*'s (2014) study, from which it takes direct inspiration for the selection of the experimental materials. At the same time, this study is a continuation of Korecky-Kröll *et al.*'s (2014) study, inasmuch as behavioral data are measured for the processing of morphonotactic sequences that are larger than the morpheme, and specifically, for tri-consonantal clusters in which C1 is part of the lexical root and C2C3 coincide with an inflectional morpheme. In this study, we run two distinct experiments: a 'split cluster' game test, and a sequence monitoring task. The two experiments were aimed at evaluating the speakers' reactions to the presence vs. absence of a morphological boundary during the phonological processing of the clusters. Given that the phonotactic and morphonotactic clusters that were compared in the experiments were homophonous (i.e., they were composed of the same segments in the same relative order), we postulated that any difference in subjects' reactions had to be traced back to different phonological representations for homophonous phonotactic and morphonotactic sequences.

Concerning the developmental issue of whether and to what extent morphonotactic knowledge help in morphological and phonological acquisition, this study tests the existence of age-related effects in processing. To that aim, we opted for testing two different groups of subjects, one of adults and another of adolescent speakers. Given the intrinsic difficulty of the selected experimental procedures, it proved impossible to include children in the design. The hypothesis was that, if homophonous phonotactic and morphonotactic clusters are differently processed, then this difference should be more visible in the production and perception of adolescents, who are still in the process of increasing the size and complexity of their lexicon and grammar, than in the adults' response.

2. Experiment 1: 'Split cluster' test

Experiment 1 was aimed at testing whether native speakers of German are sensitive to the presence of a morphological boundary within a bimorphemic cluster, when asked to produce a phonologically modified version of it. The experiment was conceived of as a language game in which the participants had to split the consonant clusters of monosyllabic words by inserting an /i/ vowel between the consonants of the cluster. In 80% of the cases, these were bi-consonantal clusters and the subjects had to insert the vowel between the first and the second consonant. In the remaining 20%, however, the items contained tri-consonantal /Cst/ clusters and the subjects had to decide whether inserting the vowel either between the C and the /s/ or between the /s/ or the /t/. For example, for a word such as *Wulst* 'bulge', the participants could either produce /'vulist/ or /'vulsit/. The experimental words included both words ending in a phonotactic cluster, such as *Wulst*, and words ending in a morphonotactic cluster (with /st/ as the second morpheme of the word, e.g. *lobst* 'you praise'). Our prediction was that for morphonotactic clusters the /Cist/ response was more frequent and/or easy than for the phonotactic ones. The reason of such expectation is that splitting the /Cst/ word-final cluster as /Cist/ corresponds to segmenting the original word into its morphological constituents (root + morphological ending; e.g. *lob-st* > *lob-i-st*), which is not the case for words containing a phonotactic cluster (where no morphological boundary is found).

2.1. Participants

Two groups of native Austrian German speakers participated in the study. The first was a group of 38 adults (age 29-52, 20 females, 18 males). The second group was composed of 26 adolescents (age 11-15, 17 girls, 9 boys) attending a high school (AHS) in Vienna. None of them reported any speech or hearing disability.

2.2. Materials

The experimental items were 14 German monosyllabic words ending in a /Cst/ cluster (in one case a /CCst/ cluster). Half of them contained a phonotactic cluster and the other half a morphonotactic one. Eight items ended in /nst/, two in /pst/, two in /lst/ and two in /ŋkst/ (an Austrian variant of /ŋst/). The items are listed in Table 1. The two classes (phonotactic vs. morphonotactic clusters) were balanced for average word frequency (calculated as the number of occurrences in the 500-million-word *Leipzig Deutscher Wortschatz Online* database).

Table 1. German monosyllabic stimuli used as experimental items in Experiment 1. Verbal forms correspond to 2nd sg present.

	Phonotactic items			Morphonotactic items		
Cluster type			Frequency			Frequency
/nst/	*Dunst*	'mist'	386	*kennst*	'know'	102
	Wanst	'paunch'	5	*kannst*	'can'	1661
	Kunst	'art'	6325	*meinst*	'mean'	102
	Gunst	'goodwill'	1388	*nennst*	'call'	21
/pst/	*Obst*	'fruits'	869	*lobst*	'praise'	94
/lst/	*Wulst*	'bulge'	20	*weilst*	'stay'	45
/ŋkst/	*Angst*	'fear'	17370	*längst*	'long ago'	19756
average			3766			3112

Fifty-six monosyllabic German words containing a bi-consonantal cluster served as fillers. Ten were /ns/-, /ps/- and /ls/-ending words (called 'CS fillers'); 6 of them were monomorphemic, while 4 contained a morphonotactic cluster. An additional group of 10 /st/-ending words ('ST fillers') also included 6 monomorphemic and 4 morphonotactic clusters. Another 10 words ended in a variety of bi-consonantal clusters (/ld, rf, nʦ, rx, rb, nt, rf, mp/; these were called 'CC fillers'). Finally, 26 words with a bi-consonantal cluster in initial position were included ('w_initial fillers').

Two experimental lists were created by pseudo-randomizing the 70 total items (14 experimental items and 56 fillers). The randomization was controlled in order to avoid the occurrence of a CS or ST filler before an experimental item; two consecutive experimental items were also banned. The participants were assigned one of the two lists in equal proportion.

Ten additional monosyllabic words ending (N = 6) or beginning (N = 4) with a biconsonantal cluster (word-final /st lf lm xs/ and word-initial /kr dr sl sn/) served for the training session.

2.3. Procedure

Experiment 1 was an offline test implemented with Presentation® on a Windows PC. The participants were requested to take part in a language game. They had to assume that, in a Martian language very similar to German, any word can be modified by inserting a /i/ vowel between the consonants of a cluster, to create diminutive and attenuative forms (e.g. *Hund* 'dog' → /'hunit/ 'small dog' or *fragen* 'to ask' → /fi'ra:gɛn/ 'to ask a few questions'). They were then presented with one of the two experimental lists and asked to insert /i/ as fast as possible whenever they found a C cluster in the word stimulus.

The stimuli were presented one at a time. Each trial began with a fixation stimulus (*****) of 500 ms, after which the word stimulus was presented, both visually (capitalized, in the center of the screen) and orally (on headphones). The duration of the visual stimulus was equivalent to the duration of the oral stimulus; each individual stimulus had a different duration, which could vary between 531 and 617 ms. The subjects were instructed to repeat the word with an /i/ between the two consonants of the cluster as soon as they could (although any response given within 3500 ms from the offset of the stimulus was taken as valid and the reaction times were not measured). They were not told that the experiment included a minority of tri-consonantal clusters.

Before the experiment, a training session consisting of 10 items with bi-consonantal clusters was presented.

2.4. Analysis

A total of 532 (adult group) and 364 (adolescent group) responses for the experimental items was analyzed. Cross-tabulations of response type ('IST' response, 'SIT' response, missing response) by stimulus type (phonotactic, morphonotactic) were realized, separately for the two age groups. The two lists did not differ for the percentage number of missing responses, nor for the overall distribution of the response types; the data of the two lists were therefore collapsed for the purposes of the present analysis.

Two-sided Pearson's Chi Square tests were run to evaluate the presence of significant differences in the distribution of the response types across groups and stimulus types.

2.5. Results

The results of the cross-tabulations are shown in Table 2. Overall, the 'IST' response was more frequent than the 'SIT' response (59% vs. 33%). The group of adults produced a lower percentage of missing responses compared to the adolescents (4% vs. 12%); this indicated that the task turned out to be not as easy for the younger participants as for the older ones.

For the group of the adult participants, no significant effect of stimulus type was found on response type (χ^2 (5, N = 532)= 1.858, $p > .05$). This meant that the splitting strategy did not change significantly as a function of the type of the cluster included in the item; the proportion of missing responses (i.e., the failure to split the cluster) was also very similar for the phonotactic and the morphonotactic items (though the former turned out to be on average slightly more difficult to split than the latter).

By contrast, in the case of the adolescents, the test revealed the presence of an uneven distribution of the different types of response. In particular, the phonotactic clusters were significantly more difficult to deal with compared to the morphonotactic ones (17.6% vs. 7.1% of missing responses, respectively) and less frequently split according to the 'SIT' response (53.3% vs. 64.3%). Such differences were statistically significant (χ^2 (5, N = 364) = 9.901, $p < .01$).

No additional effect of stimulus or consonantal context (/nst pst lst ŋkst/) on the proportion of response types was found (stimulus: adults χ^2 (20, 532) =28.729, p >.05; adolescents χ^2 (20, 364)= 35.310, p > .05; context: adults χ^2 (11, 532) =10.315, p >.05; adolescents χ^2 (11, 364)= 8.288, p > .05).

Table 2. Frequency and percentage of 'IST', 'SIT' and missing responses as a function of age group and stimulus type in Experiment 1.

		Adults		Adolescents	
		N	%	N	%
Phonotactic	missing	14	5,3	32	17,6
	'IST'	155	58,3	97	53,3
	'SIT'	97	36,5	53	29,1
	Total	266	100	182	100
Morphonotactic	missing	8	3	13	7,1
	'IST'	163	61,3	117	64,3
	'SIT'	95	35,7	52	28,6
	Total	266	100	182	100

2.6. Discussion

Experiment 1 aimed at testing whether native speakers of German are sensitive to the presence of a morphological boundary within a tri-consonantal cluster when asked to disrupt the consonantal sequence by inserting an /i/ vowel internally. In particular, it was hypothesized that for those items where a morphological boundary occurs between the first and the second consonant, the vowel was inserted precisely in that position significantly more often than for items with no internal morphological boundary. It was also hypothesized that an age effect could emerge, with younger speakers more sensitive to the difference between phonotactic and morphonotactic clusters than older speakers; to test that hypothesis, the performance of adult native speakers was compared with that of a group of adolescents.

The results showed that, overall, the subjects opted for the 'IST' response more frequently than for the 'SIT' response for both phonotactic and morphonotactic items. This result can be explained by making reference to general principles of phonotactic markedness: all other things being equal, a sequence like /CVCist/ is phonotactically less marked than a sequence like /CVCsit/ (with a word-internal obstruent-sibilant cluster). Language-specific preferences may also play a role here: word-final /-ist/ is more frequent than word-final /-sit/ in German.

A differential effect of morphological congruency in the case of the 'IST' response type was expected to hold for words with morphonotactic clusters only. In this respect, the results pointed towards the existence of a significant difference between the performance of adult participants and that of the adolescents. Only the latter, and not the former, treated morphonotactic clusters differently from their phonotactic counterparts. This was evident in two respects: first, morphonotactic clusters were easier to split; second, they were comparatively more often split according to the 'IST' option, that is, by separating the C-final root from the /st/ inflectional ending. These data can therefore be interpreted as a heavier reliance of adolescents (compared to adults) on the morphonotactic status of clusters, that is, items containing a morphonotactic cluster were easier to be divided into two parts given that they are composed of two morphemes. This is compatible with the general hypothesis that knowledge of the morphonotactic status of clusters improves the adolescents' processing of the stimuli.

To sum up, Experiment 1 demonstrated that, in an offline test requesting to produce a modified version of homophonous mono- and bi-morphemic clusters, the youngest speakers used implicit lexical and morphological information as a possible cue for the accomplishment of the phonological production task. This suggests that morpheme boundaries may indeed count as relevant information cues in differentiating homophonous clusters, as assumed under the Strong Morphonotactic Hypothesis (see above).

At the same time, this opens two further questions. The first question is whether morpheme boundaries also play some role in online, pre-lexical processing of homophonous clusters. If they do, a second question follows, and specifically, whether they play a facilitatory effect (as in the case of the offline lexical production task of Experiment 1) or an inhibitory one (as one could assume, starting from the observation that the presence of a morpheme boundary within a consonant sequence represents an additional information to process and, as such, could imply an additional processing cost).

To address these issues, Experiment 2 was conceived to investigate whether the effect of morphonotactics reported for the adolescents in the 'split cluster' test was also present in an online perceptual experiment focusing on pre-lexical processing.

3. Experiment 2: Fragment monitoring

Experiment 2 involved a slightly modified version of the sequence monitoring paradigm of Frauenfelder & Kearns (1996). This task is mostly known in the form of syllable monitoring as it was extensively used to investigate the role of syllables in speech processing and lexical access (since Mehler *et al.* 1981). In sequence monitoring tasks, subjects are presented with targets that are either congruent or incongruent with a linguistic unit in the target-bearing item. They have to decide whether the target is part of the spoken input that is presented subsequently. Congruent targets yield faster detection latencies, compared to incongruent ones. In the experiment presented here, the targets were consonant sequences such as /nst/, /pst/, /lst/ and /kst/. Consistently with the standard variant of the sequence monitoring task, the targets were presented visually, and spoken carrier words had to be monitored for the occurrence of these targets. The targets occupied the final position in monosyllabic words or the internal position in disyllabic words. As in the preceding experiment, the clusters were phonotactic in half of the cases, morphonotactic in the other half (with /st/ or /stə/ as the second morpheme, or second and third morphemes, of the word, in mono- and disyllables respectively). Our expectation was that, if morpheme boundaries play a role in the monitoring task, morphonotactic clusters are longer and less accurate to detect than phonotactic clusters, because only the former, and not the latter, are incongruent with linguistic units (in this case, morphemes) of the target-bearing item.

3.1. Participants

As in the case of the previous experiment, two groups of Austrian German native speakers participated in Experiment 2. The first group was composed of 41 adults (age 25-59, 24 females, 17 males). The second group was composed of 28 adolescents, aged 12-16, 16 girls and 12 boys, attending the same Viennese high school as those of Experiment 1. None of them reported any speech or hearing disability.

3.2. Materials and procedure

The experimental items were 30 German words containing a cluster of three (in a few cases, four) consonants in either word-final or word-medial position. The clusters were /nst/, /lst/, /pst/ and /kst/; all were phonotactic in half of the cases, morphonotactic in the other half. Eight words were disyllables with the cluster in internal position; the remaining 22 words were monosyllables with the cluster in the final position (see Table 3). The composition of the two groups (phonotactic vs. morphonotactic items) was balanced for as many parameters as possible: word length (number of syllables and of phonemes), position of the cluster (word-medial and word-final), type of cluster (/n/, /l/, /p/ and /k/ followed by /st/) and average frequency, calculated as number of occurrences in the *Leipzig Deutscher Wortschatz Online*. However, while average frequency for the phonotactic and the morphonotactic items was very similar for /nst/ and /pst/ items, it was not for /lst/ and /ŋst/ items; in the former case, morphonotactic items were more than twice as frequent as the phonotactic ones, while in the latter, they were more than 10 times less. Finally, all phonotactic clusters were immediately preceded by a short vowel, except *Papst* 'pope' and *Obst* 'fruits', where the vowel (which may be long or short in Austrian German) was realized as long. All morphonotactic clusters were immediately preceded by a short vowel, except *schonst* 'you spare', *sagst* 'you say' and *gibst* 'you give' (which may have a long or short vowel in Austrian German), where the vowel was long.

The duration of the cluster of each experimental item and the duration of the speech portion preceding the cluster were measured. The clusters' average duration for phonotactic and morphonotactic items was approximately the same. In the case of the preceding segments, there was a difference of about 15 ms (with phonotactic clusters shorter than morphonotactic ones). An independent sample t-test with cluster duration and pre-cluster duration as dependent variables and cluster type (phonotactic, morphonotactic) as grouping factor showed that the two groups of items did not differ significantly (cluster duration: t (28) = -0.173, p > .05; pre-cluster duration: t (28) = -0.973, p > .05). However, as the data in Table 3 shows, there was much variation according to cluster type. Particularly in the case of pre-cluster duration, the difference between phonotactic and morphonotactic /nst/ items was one of 64 ms (morphonotactic items having shorter pre-cluster durations), while for /lst/ items was of about 35 ms (morphonotactic items having longer pre-cluster durations); also in the case of /kst/ clusters, pre-cluster duration in morphonotactic was on average 30 ms longer than in phonotactic items.

There is currently big debate about whether seemingly homophonous segments that do, or do not, represent morphemes are phonetically identical or different. A growing amount of evidence shows indeed that subtle durational differences may cue functional distinctions between morphemic and non-morphemic segments, or between different morphemes (e.g. Plag *et al.* 2015 for a large-scale account of word-final /s/ in English). The variability found in our data for clusters and for their phonological environments could in principle hide a morpho-phonetic effect of this kind. However, our word set is too small and does not allow generalizations. We therefore limit our phonetic analysis to the observations above; since between-group durational variability could in principle affect the subjects' response, we included cluster and pre-cluster durations as predictors in the statistical model.

Table 3. Experimental stimuli used in Experiment 2. "CDur" = cluster duration (in ms); "PCDur" = pre-cluster duration (in ms); "Freq" = word frequency.

	Phonotactic items				Morphonotactic items			
Cluster type		CDur	PCDur	Freq		CDur	PCdur	Freq
/nst/	sonst	353	201	12691	schonst	355	248	6
	Wanst	396	177	22	kannst	415	146	29709
	Kunst	413	168	31593	kennst	409	147	21628
	Gunst	395	75	2715	nennst	400	177	155
	Monster	352	153	983	dünnste	275	89	62
/nst/ average		382	155	9601		371	161	10312
/pst/	Papst	271	164	16971	knipst	332	154	113
	Herbst	334	263	3484	plumpst	288	220	35
	Obst	330	145	6058	gibst	357	170	24740
/pst/ average		312	191	8837		*326*	*181*	*8296*
/lst/	Wulst	368	207	29	willst	374	155	3768
	Elster	440	73	99	hellster	441	147	4
	Polster	372	119	1431	vollste	419	208	104
/lst/ average		393	133	520		*411*	*170*	*1292*
/kst/	Text	344	113	17026	mixt	345	155	215
	Gangster	346	178	1313	längste	367	211	2423
	Angst	308	189	5737	denkst	327	159	694
	Axt	365	106	88	sagst	326	189	1069
/kst/ average		341	147	6041		341	179	441
clusters average		359	155	6683		362	171	5648

Seventy-five mono- and disyllabic German words served as fillers. There were two experimental lists. Each list was divided into 16 trials. There were 11 'go' and 5 'no-go' trials. Each 'go' trial began with the visual presentation of an orthographic string corresponding to the clusters of the experiment: these were NST (for /nst/ clusters), LST (for /lst/ clusters), PST and BST (for /pst/ clusters), and XT, GST and KST (for /kst/ clusters). This target string appeared in the middle of the computer screen, in capitals and with an appropriate font dimension, and remained visible for 2 seconds. The stimuli were 4 to 8 words of which 1 or 2 were experimental phonotactic or morphonotactic items containing the phoneme sequence indicated by the visual string (e.g. in the case of the string LST, the items contained the sequence /lst/). The others were fillers and did not contain those phonemes (neither the sequence /lst/ nor the individual phonemes /l/, /s/ or /t/). The 'no-go' trials were identical to the 'go' trials except that they did not contain any word item matching the phonological sequence indicated by the target string; the initial strings in the 'no-go' trials were FST, BST, MS and PS. The 'no-go' trials were identical in the two experimental lists. However, the 'go' trials were differentiated across lists inasmuch as, for each target string, one list contained only the phonotactic item as matching word, the other list contained only the corresponding morphonotactic item. The proportion of phonotactic and morphonotactic items as matching words was balanced in the two lists. Each list was therefore composed of 90 words (75 fillers and 15 experimental items) subdivided in 16 trials. Each list appeared with two different orders of trial presentation (two randomizations), resulting in a total of four final lists. Each subject was assigned one of the four final lists.

The oral stimuli had been produced by a male native speaker of Standard Austrian German and recorded on an Edirol 4-Channel portable Recorder and an AKG CK91 microphone with a sampling rate of 44100Hz/16 bit. After the presentation of the target string, the relevant oral stimuli were consecutively presented on headphones. For each stimulus, the subjects had to press a 'yes' key (the green button on a Cedrus response pad) if they thought that the word contained the phonemes indicated by the target string or a 'no' key (the red button) if they thought differently. The time lag for the response was 2000 msec. The target string remained visible during the presentation of the associated stimuli. The inter-trial interval was 1000 msec.

Two trials of 6 and 4 oral stimuli preceded by, respectively, ST and NZ target strings served as training session.

3.3. Analysis

The dependent variables were response latencies and accuracy. As fixed factors we considered Age (adults vs. adolescents), Frequency (= the log transformed frequency of occurrence of each experimental item in the reference corpus), ClusterDuration (in msec), PreClusterDuration (= the duration of each item stimulus from its onset to the onset of the target cluster; in msec), AntecedentRT (= the response latency of the preceding item in the experimental list; for latency analysis only), AntecedentAccuracy (= whether the preceding item yielded a correct response or an error; for accuracy analysis only), Status of the cluster (phonotactic vs. morphonotactic), and the interactions Age*Status of the cluster and Age*Frequency.

Mixed effects regressions were implemented in the packages lme4 of the software R (Bates *et al.* 2014). To bring the variation of random effects such as subject or item under statistical control, a mixed-effect model with subjects, items and cluster types as random effects was run. A factor was considered significant if its t-statistics yielded a t-value of greater than 2 (or less than -2) when included in the model, or its p-value was < .05; in addition, a likelihood ratio test compared the model including the Status of the cluster factor to a model without it; the test had to yield a p-value lower than 0.05 to show that the inclusion of the factor did significantly improve the fit of the model.

A total of 3780 responses for the adults and 2340 for the adolescents were analyzed for global accuracy, i.e. number of correct responses ('yes' button for matching words, 'no' button for non-matching words). The subsets of 630 responses for the adults and of 390 for the adolescents corresponding to the 30 experimental items were analyzed for accuracy (i.e., the number of correct identifications of the relevant fragment in the "go" trials). Of these, the correct responses (N = 556 for the adults; N = 308 for the adolescents) were also analyzed for reaction times.

3.4. Results

3.4.1. Accuracy

The analysis of global accuracy showed that, overall, the adolescents performed more errors than the adults (6% vs. 3.5%, respectively). The same result was found when we considered the subset of experimental items only: in this case, the percentage of missed identifications was 21% for the adolescents and 12% for the adults. As in the previous experiment, then, the younger speakers found the task relatively more demanding compared to the adults.

The data in Table 4 also reveal that adolescents made more errors on the morphonotactic items than on the phonotactic ones (respectively, more than 25% of the morphonotactic items were misidentified, compared to 16% of the phonotactic ones). The difference was comparatively less evident in the case of the adults' performance (13% vs. 10%), which suggested that the two groups of subjects were differently affected by the (mor)phonotactic status of the cluster in the monitoring task.

Table 4. Accuracy in the identification of experimental items as a function of stimulus type and age range. C = correct identification, E = error (missed identification of the matching fragment).

			Phonotactic	Morphonotactic	Total
Adults	C	Frequency	283	273	556
		% within Phonot./ Morphonot.	89,9	86,6	88,3
	E	Frequency	32	42	74
		% within Phonot./ Morphonot.	10,1	13,4	11,7
	Total	Frequency	315	315	630
Adolescents	C	Frequency	163	145	308
		% within Phonot./ Morphonot.	83,6	74,4	79
	E	Frequency	32	50	82
		% within Phonot./ Morphonot.	16,4	25,6	21
	Total	Frequency	195	195	390

The mixed effects logistic regressions with accuracy as dependent variable and subjects, items and cluster types as random factors was aimed to verify whether the probabilities associated to incorrect detection of clusters were associated with changes in the status of the cluster (from phonotactic to morphonotactic) and/or in the age of the participants.

The results showed that the only significant factors turned out to be Age, with adult participants significantly more accurate than adolescents, and (log transformed) Frequency, with low frequency items more frequently hit by errors than high frequency items (see Table 5). Neither the Status of the cluster factor nor the Age*Status and Age*Frequency interactions showed up as statistically significant.

The observed differences in the average accuracy scores, therefore, could not be confirmed by the mixed effects logistic regression statistics.

Table 5. Fixed-effect coefficients and *p* values in the mixed-effects model fitted to accuracy (subjects, items and cluster types as random factors). The reference levels for the categorical predictors are the following: for Age it is 'adolescents', for Status of the cluster it is 'morphonotactic'. All coefficients can be interpreted as changes relative to these reference levels.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.126	1.5383	0.082	0.934
Ageadult	-0.822	0.275	**-2.978**	**
Frequency	-0.111	0.0378	**-2.942**	**
AntecedentAccuracy	0.277	0.710	0.391	0.695
PreClusterDuration	0.002	0.002	0.923	0.356
ClusterDuration	-0.003	0.003	-0.988	0.322
Statusphono	-0.368	0.268	-1.372	0.170
Ageadult*Statusphono	0.247	0.363	0.682	0.495
Ageadult*Frequency	0.222	0.267	0.685	0.345

3.4.2. Reaction times

In the mixed-effect model with subjects, items and cluster types as random factors and latencies as dependent variable, we wanted to verify whether the phonotactic or morphonotactic status of the cluster affected the subjects' reaction times in the detection task, and whether this effected was modulated by the age factor. Figure 1 shows by means of boxplots that for both groups of subjects, the median lines are higher for the morphonotactic than for the phonotactic items; but there seems to be a bit more overlap (and more dispersion) in the adolescents' performance than in the adults' one.

The results of the mixed model are shown in Table 6. There were, as expected, significant effects of (log transformed) Frequency (higher frequency items faster than lower frequency items), AntecedentRT (the faster the antecedent item, the faster the target item), and PreClusterDuration (the longer the duration of the stimulus up to the cluster's onset, the longer the time needed to give the response). The duration of the cluster, by contrast, did not affect the model. Age yielded a significant result, with adult participants reacting faster than adolescents (195 msec on average). Most importantly, our predicted explanatory variable Status of the cluster also yielded a significant result, showing that phonotactic clusters were detected on average 73 msec earlier than the corresponding morphonotactic ones. However, the interaction Age*Status was not significant, suggesting that the two groups of participants were equal in showing shorter latencies in the detection of the phonotactic clusters.

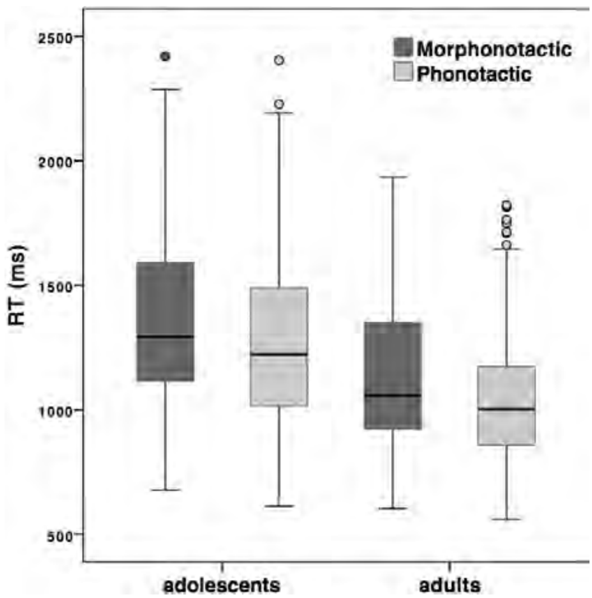

Figure 1. Relationship between age groups and the status of the cluster (phonotactic, morphonotactic). (Error bars represent confidence intervals of the individual categories.)

Another interesting result was related to the Age*Frequency interaction, which turned out to be very close to significance. In order to assess the explanatory contribution of item frequency to response latencies in the two groups of speakers, two linear regression models for the two subject groups were run. For the group of the adult speakers, the two variables turned out to be negatively and significantly correlated (Pearson correlation coefficient $r = -0.211$, $r^2 = 0.45$; $F (1,542) = 25,256$, $p < .0001$). This meant that the higher the word frequency, the shorter the time needed to detect the cluster in the word, as expected. For the group of the adolescents, by contrast, the two variables turned out not to be significantly correlated (Pearson's correlation coefficient $r = -0.105$, $r^2 = 0.16$; $F (1,295) = 2,655$, $p > .05$). Therefore, in the adolescents' performance, the response speed was in no way influenced by the fact that the target sequence could occur in high vs. low frequency words. These data suggested slightly different processing strategies in cluster detection for different age groups.

Table 6. Fixed-effect coefficients and *p* values in the mixed-effects model fitted to RT (subjects, items and cluster types as random factors). The reference levels for the categorical predictors are the following: for Age it is 'adolescents', for Status of the cluster it is 'morphonotactic'. All coefficients can be interpreted as changes relative to these reference levels.

Coefficients	Estimate	Std. Error	t value
(Intercept)	1250.470	114.508	10.920
Ageadult	-194.843	49.280	-3.956
Frequency	-13.158	3.502	-3.757
AntecedentRT	0.225	0.038	5.961
PreClusterDuration	0.471	0.182	2.586
ClusterDuration	-0.357	0.239	-1.489
Statusphono	-73.464	27.484	-2.673
AgeGroupadult*Statusphono	8.013	33.742	0.237
AgeGroupadult*Frequency	-0.348	0.221	-1.989

We additionally checked the effect sizes of the explanatory variable by fitting a 'null' model that lacked the Status of the cluster predictor, and considered whether the difference between the likelihood of these two models (the full and the 'null' model) is significant. The results of the likelihood ratio test confirmed that the morphonotactic status of the clusters significantly affected reaction times ($\chi^2(2)=16.75$, $p=0.00023$).

3.5. Discussion

Experiment 2 was aimed at testing whether native speakers of German were sensitive to the presence of a morphological boundary within tri-consonantal clusters when asked to identify them as fast as possible in isolated words presented orally. In particular, it was hypothesized that, if morphological boundaries played a role in cluster detection, morphonotactic clusters were slower and less accurate, due to the fact that the first consonant pertains to the lexical morpheme composing the word while the second and third consonants form (part of) the inflectional morpheme. While Experiment 1 provided some evidence in support of the morphonotactic hypothesis by pointing to the facilitatory effect of morphological structure in cluster modification (production), Experiment 2 was expected to test the role of morphonotactics in pre-lexical phonological processing (perception). As in Experiment 1, it was also hypothesized that an age effect could emerge, with younger speakers more sensitive to the morphonotactic status of clusters than older speakers; in order to test that hypothesis, the performance of adult native speakers was compared with that of a group of adolescents. Unlike Experiment 1, in which the participants had no temporal restriction for the execution of the task, Experiment 2 tested the online processing of clusters by constraining the temporal interval allowed for the response.

The first expectation, concerning the difference between phonotactic and morphonotactic clusters, was confirmed by the reaction time analysis, but not by the accuracy analysis. In addition, the effect that was found on latencies was an inhibitory one. Morphonotactic items turned out therefore to be slower, but not less accurate, to be detected than phonotactic items. The latency results can thus be interpreted in support of the morphonotactic hypothesis, inasmuch as the presence of a morphological boundary within consonant clusters turned out to affect the speakers' time of recognition of those clusters; since this effect was inhibitory, the result also support the view that, in this online perceptual experiment, morpheme boundaries represented an additional processing cost during the phonological processing of the items.

The second expectation, concerning different processing strategies by different age groups, was basically disconfirmed by the results of Experiment 2, although the data were not entirely clear. In the accuracy analysis, the Age*Status of the cluster interaction was not significant, though the average values pointed to an existing trend for adolescent speakers to produce more errors on the morphonotactic items than on the phonotactic. In the latency analysis, the interaction was equally insignificant, though the adolescents turned out to be overall insensitive to word frequencies. The latter point is worth of further comment.

In the adolescents' performance, the apparent independence of reaction times from lexical frequencies could suggest that, when performing the sequence monitoring task, these participants accessed the phonological representation of the cluster without necessarily relying on the lexical representation of the whole word. For them, lexical properties such as whole word frequency were indeed irrelevant. Then, if we consider once again that the sequence monitoring task is based on the assumption that congruent targets yield faster detection latencies than incongruent targets, and that in Experiment 2, consonantal sequences appearing in multimorphemic words were said to be incongruent with the morphemic structure of the word, the frequency result on adolescents would provide indirect support to a view of morphological processing in which individual morphemes are recognized early, and morphemic representations are activated prior to the activation of lexical entries (from Taft & Forster 1975 onwards, with different versions of the dual-route approach, particularly as far as morpho-orthographic representations are concerned; e.g. Caramazza *et al.* 1988, Longtin *et al.* 2003, Taft & Ardasinski 2006).

4. General discussion and conclusions

By comparing the behavior of adults and adolescents in splitting, modifying and detecting tri-consonantal phonotactic and morphonotactic sequences of their native language, the two experimental studies presented here aimed to investigate the processing of phonotactic sequences that straddle a morphological boundary, in comparison to homophonous monomorphemic sequences.

Experiment 1 demonstrated that, when asked to disrupt a consonantal sequence and introduce an /i/ vowel at some point between two consonants of the cluster, part of the speakers took advantage of the information related to the morphological structure of the word, thus inserting the vowel preferentially at the point of the morphemic juncture; and in general, bimorphemic clusters were easier to split and modify than monomorphemic ones. This result provided support to the general claim that the speakers are sensitive to the phonotactic vs. morphonotactic status of homophonous consonant clusters, and may use this information in processing the phonological and morphonological characteristics of words. The fact that such sensitivity was found in adolescents only, not in adults, also pointed to age-related differences in (mor)phonotactic processing. As a matter of facts, it is well known that the acquisition of phonology starts earlier and is mastered earlier than the acquisition of morphology; as a consequence, the interaction between these two components necessarily changes in early childhood (Dressler & Dziubalska-Kolaczyk 2006; Bavin 2009). Additionally, bootstrapping between phonology and morphology is limited to early phases of acquisition (Weissenborn & Höhle 2000). However, our data from Experiment 1 only indirectly support this view, inasmuch as it is not entirely clear, first of all, whether and to what extent adolescents also differ from pre-pubescent children. Second, similar age-related differences in (mor)phonotactic processing were neither consistently nor significantly found in Experiment 2, contrary to the expectations.

Capitalizing on the suggestions coming from Experiment 1 that adolescents differed from adults in the way they exploited morphonotactic information in producing phonologically modified consonant clusters, Experiment 2 aimed at verifying whether the same sensitivity to the clusters' (mor)phonotactics was equally present in the online pre-lexical processing of phonological sequences. The results of Experiment 2 were consistent with those of Experiment 1 inasmuch as phonotactic and morphonotactic clusters were processed differently (i.e., the former elicited shorter reaction times than the latters), but diverged to the extent that the response pattern was generalized to adults too. Adults and adolescents did differ, to the extent that the latter were overall less accurate and slower than the former; but this was indicative of a higher processing cost associated to the accomplishment of the experimental task for adolescents as compared to adults; age differences did not influence the way the speakers processed the contrast between morphonotactic and phonotactic cluster. Furthermore, while Experiment 1 showed that morphonotactic clusters were easier to split and produce (with the addition of an /i/ vowel) than phonotactic ones, Experiment 2 showed that morphonotactic clusters were slower to be detected than phonotactic ones (though eliciting an equal number of correct and incorrect responses).

Taken together, these results indicate that morphonotactics can be relevant in phonological processing, but its influence varies as a function of experimental task, and, in some experimental tasks, according to the age of the speakers. In online phonological processing, morphonotactic sequences may involve an additional processing cost compared to homophonous phonotactic sequences. This processing cost may be the same for adults and for younger speakers. Korecky-Kröll *et al.* (2014), also on German, demonstrated that adult native speakers actively exploit the potential boundary signaling function of clusters that result from morphological concatenation, by treating morphologically produced clusters differently than morpheme internal clusters. The results of Experiment 2 consistently showed that the two types of clusters can be processed differently by both adolescents and adults. The fact that in the study by Korecky-Kröll *et al.* (2014) the morphonotactic sequences were advantaged in processing, compared to the phonotactic ones, was due to the fact that those subjects were asked to detect phonemes or sequences that were either separated from the stem by a morphological boundary, or not; these sequences did not straddle a morphological boundary. In our Experiment 2, by contrast, morphonotactic clusters were incongruent with the monitoring target, which could explain their disadvantage in processing. Therefore, both the present study and the one of Korecky-Kröll *et al.* (2014) consistently support, from two different perspectives, the observation that the presence of a morphological boundary is relevant to the speakers in their processing of consonantal clusters of their native language.

The present findings are also consistent with the results of the psycho-computational study of Calderone *et al.* (2014), in which the phonological representation of morphonotactic sequences and of homophonous phonotactic ones were derived from an artificial algorithm trained on German phonotactics and turned out to be significantly different, independently from any quantitative parameter of phonotactic probability or lexical frequency. In that paper it was hypothesized (Calderone *et al.* 2014: 69) that the early phases of lexical and morphological processing are characterized by automatic parsing attempts and the need to extract as much information as possible from language input, thus enabling "the activation of all meaningful units of language" (Libben 2010; see also Dressler *et al.* 2003).

The offline and online experiments on adults and adolescents reported on here confirm that morphology may impact phonotactic processing inasmuch as homophonous sequences that either are monomorphemic or straddle a morphological boundary can be differently perceived, produced, manipulated. Additional testing with different experimental tasks and populations will provide more details on whether such parsing strategy is exclusive of early acquisition phases (or may also be effective in general processing), and on when and how the speakers' sensitivity to the (mor)phonotactic status of clusters has facilitatory, inhibitory or no effects of phonological, morphological, lexical processing.

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