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Brain and Language xxx (2004) xxx–xxx

Brain and Language

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Effects of syllable-frequency in lexical decision and naming: An eye-movement study☆

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Accepted 8 June 2004

Abstract

In three experiments we explored task-specific effects of syllable-frequency, following Perea and Carreiras' (1998) findings of a facilitative effect during naming and an inhibitory effect during lexical decision. In Experiment 1, an inhibitory effect of first syllable-frequency on articulation duration suggested a process-specific effect during naming: a facilitative effect on construction of phonological output, but an inhibitory effect on lexical access. Eye-movement recording was used in Experiment 2 to disentangle these two processes. An inhibitory effect on eye-movement parameters during both lexical decision and naming supported the assumption that higher first syllable-frequency inhibits lexical access. Implications of a general inhibitory effect of syllable-frequency for computational models of word recognition, specifically for the multiple-trace memory (MTM) model of polysyllabic word naming (Ans, Carbonnel, & Valdois, 1998), are discussed.

1. Introduction

The first to report an inhibitory effect of syllable-frequency in lexical decision tasks were Carreiras, Álvarez, and de Vega (1993). Whereas a growing body of evidence supports this effect during lexical decision and perceptual identification tasks (Carreiras et al., 1993; Carreiras & Perea, 2002; Conrad & Jacobs, 2004; Mathey & Zagar, 2002; Perea & Carreiras, 1995, 1998), evidence concerning the effect of syllable-frequency during naming is contradictory, leaving open the possibility for both, facilitative (Perea & Carreiras, 1998) or inhibitory effects (Carreiras et al., 1993). In the present study, eye-movement recordings were used during a naming task to disentangle differential effects of syllable-frequency on lexical access and the production of phonological output, suggesting an inhibitory effect of syllable-frequency on lexical access also during naming. Eye movements (in contrast to response times and onsets of articulation) provided a more direct comparability between naming and lexical decision tasks not present in previous studies.

The role of the syllable as a processing unit for multisyllabic words was already discussed by Taft (1979) and Taft and Forster (1976). From their viewpoint, multisyllabic words are accessed via their first syllable, which has an independent status in the orthographic lexicon. The syllable appears to play an important role in the visual recognition of multisyllabic words in orthographies with clearly defined syllable boundaries (for review, see Carreiras & Perea, 2002). Subsequently, evidence for an inhibitory effect of the positional frequency of the first syllable was provided for lexical decision tasks (Carreiras et al., 1993; Carreiras & Perea, 2002; Conrad & Jacobs, 2004; Mathey & Zagar, 2002; Perea & Carreiras, 1998) as well as for a perceptual identification task (Perea & Carreiras, 1995).

On the basis of this effect the authors concluded, that "any model of lexical access has to incorporate a syllabic

☆ We thank three anonymous reviewers for their excellent comments and suggestions. Furthermore, we thank Angelika Ingram, Monika Parhamer, and Edith Willburger for their help during data acquisition and Melissa Võ for proofreading the manuscript.

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doi:10.1016/j.bandl.2004.06.001

level of representations or include the syllable as a sublexical unit of processing in Spanish'' (Álvarez, Carreiras, & Taft, 2001). Based on the architecture of a verbal, non-implemented interactive activation model of visual word recognition, the inhibitory effect of syllable-frequency was accounted for by increased lateral inhibition of the level of whole word entries in the mental lexicon. Syllabic units, extracted from the orthographic input, would activate whole words that contain a given syllable. More competing candidates sharing the initial syllable of a target word—referred to as syllabic neighbors—would be activated and thus inhibit the processing of the target word when (first) syllable-frequency is high. The scope of Carreiras et al.'s conclusion was widened to other, non-Romance languages by a recent study of Conrad and Jacobs (2004) who found an inhibitory effect of syllable-frequency for the German orthography during a lexical decision and a perceptual identification task.

Although this effect of syllable-frequency seems to be a reliable result across different orthographic systems, it also seems to be task-dependent and thus its exact nature remains to some degree unclear. In lexical decision tasks, response times are usually found to be longer for words with a high-frequency first syllable than for words with a low-frequency first syllable. This inhibitory syllable-frequency effect is more pronounced for low-frequency words than for high-frequency words (Carreiras et al., 1993; Conrad & Jacobs, 2004; Perea & Carreiras, 1998). Similarly, an inhibitory effect of syllable-frequency can be observed in perceptual identification tasks (Conrad & Jacobs, 2004; Perea & Carreiras, 1995). In contrast to this clear-cut pattern of results for lexical decision and perceptual identification tasks, the evidence concerning the effect of syllable-frequency during naming tasks is rather contradictory. In a first study, Carreiras et al. (1993) reported an inhibitory effect of syllable-frequency during a naming task. However, this effect was reliable only in subject analysis in one experiment and diminished in a second experiment. In another study, Perea and Carreiras (1998) reported a facilitative effect of syllable-frequency during a naming task.

In contrast to lexical decision tasks, naming tasks also require the generation of phonological output. There is evidence that frequency of occurrence not only affects lexical access, but also the speed of construction of phonological output. Using a naming task, Balota and Chumbley (1985) could show an effect of word-frequency not only during immediate, but also during delayed naming. This effect of word-frequency during delayed naming suggests that—as the authors stated—''a large component of the frequency effect in the pronunciation tasks involves production rather than simple lexical access.''

Thus, two processes involved in naming could be affected differentially by syllable-frequency. On the one hand, there is the inhibitory effect of syllable-frequency on lexical access—well established in lexical decision and perceptual identification tasks. In terms of a verbal model of interactive activation, lexical candidates would mainly be activated by a word's first syllable whereas subsequent syllables would be used to identify the appropriate lexical entry amongst these preactivated candidates. The assumption that the first syllable plays the most important role when polysyllabic words are accessed was also made by Taft and Forster (1976). Thus, the frequency of a word's first syllable would produce inhibitory effects on lexical access, which can be explained by increased lateral inhibition from a greater amount of words, activated by a high-frequency syllable. On the other hand, there could be a facilitative effect of syllable-frequency on the construction of phonological output in naming tasks: If the organization of phonological output follows a syllabic structure, as stated, for example, by Ferrand, Segui, and Grainger (1996), then syllables that are used more frequently should be easier to process at this level. As a consequence, the corresponding phonological output for words with a high-frequency first syllable could be constructed more rapidly than for words with a low-frequency first syllable. Strong evidence for this claim is provided by a study of Carreiras and Perea (2004), who report a clear facilitative effect of syllable-frequency in a series of three naming experiments with non-words (for which no lexical access is necessary or possible).

Despite a growing body of evidence suggesting an inhibitory effect of first syllable-frequency on lexical access, up to now, computational models of word recognition cannot account quantitatively for the effect (see Conrad & Jacobs, 2004). Before incorporating a syllabic level of representation in computational models, it would be helpful to know the exact nature of the syllable-frequency effect, not only during lexical decision tasks, but also during naming. One complicating factor is that the measures used for naming and lexical decision tasks are not directly comparable. Responses produced in lexical decision and naming tasks are possibly based on at least some different processing levels. Under normal conditions, a lexical decision task requires lexical access to be completed before a response takes place (but see Grainger & Jacobs, 1996; Jacobs, Graf, & Kinder, 2003 for possible exceptions). During naming, the situation is somewhat more complicated. Regular words can be pronounced before completion of lexical access (Andrews & Heathcote, 2001, see also Hennessey & Kirsner, 1999, for a more detailed discussion). Especially in shallow orthographies with their rather straightforward grapheme–phoneme correspondence, where readers can strongly rely on rules that determine correct reading, it remains unclear to what degree inhibitory effects of syllable-frequency on lexical access might be masked or even ruled out by production processes in the measure *onset of articulation*. Nevertheless, the only articulation measure that was used for the exploration of the syllable-frequency effect in reading aloud tasks is onset of articulation.

Because the empirical evidence concerning the effect of first syllable-frequency during naming is somewhat contradictory up to now, Perea and Carreiras (1998) stated that more evidence is necessary to provide a full account of the effect of syllable-frequency during naming. The goal of the present study was to provide a more direct comparison between syllable-frequency effects in lexical decision and naming tasks by using two methodological extensions (several articulation time measures and eye-movement recordings) with respect to previous studies. This should help to clarify the processes underlying the effect and to constrain future computational models of word recognition that should be able to explain the effect. First, we measured not only the latency of onset of articulation, but also the duration of articulation as a dependent variable in the naming task. *Duration of articulation* is a measure that might provide supplementary information concerning the effect of syllable-frequency during reading aloud (for a more detailed discussion on articulation duration, see Section 2.3). Second, in addition to measuring response times, we examined the eye-movement pattern of our participants in Experiments 2 (A) and (B). Besides being more strongly related to the natural process of reading than response times during lexical decision, this method allows a more direct comparison of performance in a naming and in a lexical decision task.

2. Experiment 1

Until now, the effect of the frequency of the first syllable of polysyllabic words on naming has only been examined for the Spanish orthography (Carreiras et al., 1993; Perea & Carreiras, 1998). First, the aim of Experiment 1 was to examine the effect of syllable-frequency during naming in a non-Romance language, German, that had been shown to produce an inhibitory effect in lexical decision and perceptual identification (Conrad & Jacobs, 2004). The stimulus material was almost identical to that used by Conrad and Jacobs (2004). Second, because the onset of articulation is proposed to be affected by syllable-frequency in both a facilitative and an inhibitory way, in Experiment 1 not only the onset of articulation, but also duration of articulation was used as a dependent measure. This variable has not been explored for effects of syllable-frequency during reading aloud up to now.

2.1. Method

2.1.1. Participants

In this experiment, the 18 participants (five male) from the area of Salzburg ranged in age from 22 to 42 years and were $M = 27$; 4 (years; month) old. All were German native speakers, had normal or corrected to normal vision and did not receive a reward for participation.

2.1.2. Apparatus

Verbal response was obtained with a microphone connected to a voice-key which is based on a Motorola M68C11-E micro-controller, enabling real-time detection of articulation onset and duration with a temporal resolution of 4 ms. The voice-key was triggered by a Pentium II (400 MHz) computer that was used for stimulus presentation. Stimuli were presented in Arial font in yellow color on a black background on a 17 in. Belinea monitor. Letter size of reading material corresponded to 12 point size fonts.

2.1.3. Design and stimulus material

Four experimental conditions were realized by the orthogonal combination of two factors, word-frequency and positional frequency of the first syllable (hereafter syllable-frequency). Of the overall 80 bisyllabic words, 40 were of high- and 40 were of low word-frequency (see Table 1).

The inclusion criterion for high-frequency words was an occurrence of at least 100 per million, for low-frequency words it was an occurrence of maximal 10 per million (obtained from the CELEX database, Baayen, Piepenbrock, & van Rijn, 1993). Half of the words of both word-frequency blocks were of high or low first

Table 1
Characteristics of stimulus material

	High word-F		Low word-F	
	High syllable-F	Low syllable-F	High syllable-F	Low syllable-F
N	20	20	20	20
Word-frequency [per million]	180	191	4	3
First SF [per million]	12,646	393	11,043	192
Second SF [per million]	821	857	1155	430
Neighborhood size [*N*]	.90	1.15	1.25	1.10
Letter length [*N*]	5.75	5.70	5.70	5.80

Note. Word-F, word-frequency; Syllable-F, syllable-frequency.

syllable-frequency, respectively. Syllable-frequency was defined as summed positional frequency, i.e., the summed frequency of occurrence of all words that contain a given syllable in the same position. Syllable-frequency was at least 2600 per million for items with high syllable-frequency and maximal 800 per million for items with low syllable-frequency. As evident from Table 1, the four experimental conditions were matched for summed positional frequency of the second syllable, for number of orthographic neighbors and for word length. None of the words had higher-frequency orthographic neighbors.

2.1.4. Task and procedure

Stimuli were presented word by word in lowercase letters (with appropriate capitalization), centered on the computer screen, with a fixation cross preceding each stimulus. Participants were instructed to read aloud the stimulus material as rapidly and as accurately as possible. The stimulus remained on the computer screen until the offset of the articulation was registered.

2.2. Results

Mispronunciations, responses contaminated with coughs or loss due to equipment failure led to the exclusion of 2.27% of the data. Furthermore, responses for onsets or offsets of articulation that deviated more than $SD = 2.5$ from the mean of each category for the corresponding participant were excluded from analysis (3.99% of the remaining data). Onset of articulation and duration of articulation were analyzed. The stimulus material was not matched for initial phoneme. Treiman, Mullennix, Bijeljac-Babic, and Richmond-Welty (1995) demonstrated that the initial phoneme accounts for a large portion of variance in naming latencies (onset of articulation). To control for such an influence, characteristics of the initial or final phoneme (e.g., voicing) were treated as regressors in a multiple regression, which was applied separately to onset of articulation and duration of articulation. Subsequently, the effect that was found to result from these regressors was removed from the raw data (for a more detailed description of number and type of the used regressors refer to Sections 2.2.1 and 2.2.3 of the respective measure). As indicated in Table 2, the correction led only to small changes.

Subsequent to correction of raw data, 2×2 ANOVAs were computed separately for the two measures (i.e., onset of articulation and duration of articulation) with syllable-frequency (high vs. low) and word-frequency (high vs. low) as factors. As outlined in Section 2.1, stimulus material varied in syllable-frequency (high vs. low) and word-frequency (high vs. low). The effect of these factors was examined using separate 2×2 ANOVAs for the three measures (i.e., number and duration of the first fixation and gaze duration). Analysis was done using participants (F_1) and items (F_2) as cases: In the F_1 analysis both factors were treated as within-participant factors. Effects that proved to be reliable in this analysis were tested in a subsequent F_2 analysis for generalizability over items. In this latter analysis both factors were treated as between-item factors. The relevant means for onset of articulation and for articulation duration are presented in Table 2.

2.2.1. Onset of articulation: Correction

To correct raw data of onset of articulation, two characteristics of the initial phoneme—that is voicing and glottal—were considered and coded binary (e.g., glottal vs. non-glottal). Removal of these two regressors from the raw data resulted in slight changes in means. The corrected means and the changes resulting from the correction are presented in Table 2.

2.2.2. Onset of articulation: Results

As can be seen in Table 2, the critical main effect of syllable-frequency was not reliable, $F_1 < 1$. However, onset of articulation was later for low-frequency words than for high-frequency words, $F_1(1,17) = 9.38$; $MSE = 1690$; $p < .007$ and $F_2(1,76) = 18.30$; $MSE = 872$; $p < .001$. No interaction between syllable-frequency and word-frequency was found, $F_1 < 1.41$.[1]

2.2.3. Articulation duration: Correction

To correct raw data for duration of articulation, characteristics of the initial and of the final phoneme were considered as well as the number of phonemes of the stimulus material. For both the initial and final phoneme, voicing and glottal were entered as regressors, resulting in overall five regressors. The corrected means and the changes resulting from correction are presented in Table 2.

2.2.4. Articulation duration: Results

As evident from Table 2, the critical inhibitory main effect of syllable-frequency was reliable, with a longer articulation duration for words with a high-frequency first syllable, $F_1(1,17) = 16.16$; $MSE = 547$; $p < .001$ and $F_2(1,76) = 4.54$; $MSE = 2101$; $p < .036$. Furthermore, there was a reliable main effect of word-frequency, with high-frequency words exhibiting a shorter articulation duration than low-frequency words, $F_1(1,17) = 11.69$; $MSE = 1132$; $p < .003$ and $F_2(1,76) = 7.38$; $MSE = 2101$;

[1] To examine, whether the shape of the distributions of the measure onset of articulation varies for the two syllable-frequency conditions, a response time distribution analysis was conducted. Quantile maximum likelihood estimation (Heathcote, Brown, & Mewhort, 2002) was used to fit an ex-Gaussian distribution (i.e., a convolution of a normal distribution with mean μ and standard deviation σ and an exponential distribution with mean τ) to the individual subjects distributions of onset of articulation of high and low syllable-frequency items, using 5% quantiles. A pairwise comparison revealed no differences for the three parameters μ, σ, and τ, all ts < 1.

Table 2
Uncorrected and corrected means (standard deviations) for onset and duration of articulation during the naming task in Experiment 1

	High word-F		Low word-F	
	High syllable-F	Low syllable-F	High syllable-F	Low syllable-F
Onset				
Uncorrected	550 (103)	564 (106)	580 (119)	585 (127)
Corrected	552 (103)	558 (106)	587 (119)	582 (127)
Duration				
Uncorrected	412 (98)	389 (103)	446 (79)	423 (90)
Corrected	414 (99)	391 (103)	440 (79)	419 (90)

Note. Word-F, word-frequency: Syllable-F, syllable-frequency.

$p < .008$. The syllable-frequency by word-frequency interaction was not reliable, $F_1 < 1$.

2.3. Discussion

No effect of first syllable-frequency could be observed in the naming task as concerns the measure onset of articulation (i.e., naming latency). However, this null effect during naming can be explained in terms of two opposite effects (cf. Perea & Carreiras, 1998): The assumed facilitative effect of first syllable-frequency on the construction of phonological output and the inhibitory effect on lexical access possibly were of equal strength and thus canceled each other out. The existence of two opposite effects might be the reason for the contradictory evidence concerning the effect of syllable-frequency on onset of articulation in previous studies. Thus, perhaps misleadingly, in Experiment 1, a null effect of syllable-frequency was observed, although syllable-frequency possibly affected onset of articulation. The general problem of one factor having differential effects on two processes involved in one task was discussed by Balota and Abrams (1995). Addressing the problem of wrongly assuming a null effect instead of two opposite effects, the authors stated, "that conclusions based exclusively on effects at the moment of response onset are limited." Furthermore, it was suggested that "one may be able to learn more about mental activity by continuous sampling of behavior *after* response initiation has occurred." In fact, Balota and Abrams (1995) could show that during a lexical decision task, both onset and duration of an arbitrary speech response (which indicated lexicality) were modulated by word-frequency.

The assumption that *duration of articulation* (a measure succeeding *onset of articulation*) might be a sensitive measure for the exploration of speech production was already put forward by Levelt and Wheeldon (1994). In a series of three experiments, the authors could show that production (*onset* as well as *duration*) of articulation was facilitated during the naming of arbitrary symbols that were associated with words ending in higher-frequency syllables compared to the naming of symbols that were associated with words ending in lower frequency syllables. This effect was described as independent of and additive to the effect of word-frequency. Although the authors could show the sensitivity of articulation duration for syllable-frequency, it is important to state that: (a) concerning processes related to lexical access, different consequences have to be expected during reading and during the naming of arbitrary symbols and (b) as already stated in Section 1, different consequences have to be expected due to the manipulation of the first syllable compared to the manipulation of second or third syllable. Actually, also the Spanish research group that discovered the inhibitory effect of first syllable-frequency, showed that the frequency of the second or third syllable of polysyllabic words tends to produce facilitative rather than inhibitory effects in lexical decision (Álvarez, de Vega, & Carreiras, 1998; for different effects of priming with first or second syllables see also Álvarez, Carreiras, & de Vega, 2000).

Thus, we found it useful to examine response dynamics beyond the initiation of the response and therefore also analyzed *duration of articulation*. Indeed, an inhibitory effect of syllable-frequency on duration of articulation was observed in Experiment 1. High-frequency first syllables led to prolonged articulation duration and the effect hold true for both low- and for high-frequency words. Duration of articulation seems to be sensitive to effects on early processing stages, that is, processes prior to lexical access (Hennessey & Kirsner, 1999). These results then suggest that in the process of naming a word, there is an inhibitory effect of syllable-frequency. However, this inhibitory effect seems to be effective not only before, but also *after* the initiation of a verbal response.

3. Experiment 2 (A)

The results of Experiment 1 suggested that not only during lexical decision tasks, but also during naming, syllable-frequency has an inhibitory effect. However, Experiment 1 also suggested that onset of articulation (since it seems to be affected by both facilitative and inhibitory effects of syllable-frequency) might not be the most appropriate measure to investigate the effect of syllable-frequency during naming. Consequently, we came upon a more appropriate measure for further investigations of the syllable-frequency effect during naming as well as for a direct comparison of the effects of syllable-frequency during naming and lexical decision. Eye-movement recordings could be such a measure, having the advantage of being comparable for both naming and lexical decision tasks.

The main aim of Experiment 2 (A) was to examine the effect of first syllable-frequency on eye-movement patterns during a lexical decision task. Whereas the inhibitory effect of syllable-frequency on response times during a standard lexical decision task with item-per-item presentation was reported in several studies (Carreiras et al., 1993; Conrad & Jacobs, 2004; Perea & Carreiras, 1998), in the present experiment eye movements were recorded during a lexical decision task, realized by list-wise presentation of the stimuli. Beyond the well-documented effect of word-frequency (for review, see Rayner, 1998), we also expected to observe an effect of syllable-frequency in the eye-movement pattern.

3.1. Method

3.1.1. Participants

The 11 participants (six male) from the area of Salzburg were German native speakers, had normal or corrected to normal vision and did not receive a reward for participation. Mean age was 35; 8 (years; month), ranging from 24 to 48 years.

3.1.2. Apparatus

Eye movements were recorded every 20 ms from the left eye in a natural binocular viewing situation with an ISCAN (Model RK-464) video-based eye tracking system. Participants sat at a distance of 120 cm in front of a Belinea 21 in. Computer monitor connected to a Pentium II (233 MHz) computer used for stimulus presentation. Letter size of reading material on the monitor was chosen in such a way that it corresponded to the reading of a text of 12 point size (i.e., height 3 mm for upper case letter) at a distance of 30 cm. The resulting visual angle was .6° and capital letters were 12 mm high on the monitor. Items were presented in yellow color on black background in a dimly illuminated room. The brightness of the monitor was adjusted to a comfortable level and was the same for all participants. The participants' head was fixed by a head rest to avoid head movements. An initial calibration of the system took about 2 min. To verify whether eye movements could reliably be superimposed on the stimulus material, a validation screen containing nine crosses arranged in three horizontal lines was presented after each task screen. Inspection of the eye movements on the validation screens led to the exclusion of one participant for which track loss during the recording was detected. For the remaining participants high quality of calibration was achieved and fixations could be reliably superimposed on the items of each screen.

3.1.3. Design and stimulus material

The same 80 words as in Experiment 1 were used as stimulus material. Additionally, 80 pseudowords were derived from the words by exchange of syllables to allow a lexical decision.

3.1.4. Task and procedure

For the lexical decision task, the participants were shown the 80 experimental stimuli, the 80 pseudowords, and 80 additional filler items. These 240 items were presented in lowercase letters (capitalization was used where appropriate in the German orthography, i.e., for nouns) on seven screens in comma separated lists. Each screen contained 36 items in six lines (the last screen contained 24 items in four lines). Six items were presented in each line. Filler items were placed in the first and in the last position of each line to avoid effects of line sweep on the eye movements on the experimental stimuli. The remaining four items of each line were randomly selected from the experimental stimuli and the pseudowords.[2] Participants were instructed to scan through the stimulus material from left to right, beginning with the first line. The task was to indicate the lexicality of an item in the following way: If (and only if) a pseudoword was discovered, participants had to press a button of a response box. Thus, participants had to perform a go/no-go lexical decision task with pseudowords. To familiarize participants with the task, a training screen with two lines preceded the task.

3.2. Results

Eye movements on the 80 experimental stimuli were submitted to analysis. Because it is of only limited value to analyze only one eye-movement measure (Rayner, 1998), in the present experiment three dependent mea-

[2] There is evidence that eye-movement patterns on experimental stimuli (foveal stimuli) can be influenced by the familiarity of the initial letters and the length of the items following the experimental stimuli (parafoveal items). To control for potential parafoveal-on-foveal effects (for review, see Kennedy, 2000; Rayner, 1998), bigram frequency of the initial two letters of the items following the experimental stimuli was submitted to a 2×2 ANOVA (based on experimental stimuli) with the factors word-frequency (high vs. low) and syllable-frequency (high vs. low). Neither the main effects nor the interaction were reliable, all Fs < 1. The mean letter length of the items following the experimental stimuli was close to identical (high word-frequency [WF]/high syllable-frequency [SF]: 5.75; high WF/low SF: 5.70; low WF/high SF: 5.70; low WF/high SF: 5.80).

sures were analyzed: Number of fixations, duration of the first fixation on an item, as well as gaze duration. Number of fixations was the sum of all successive fixations on a stimulus, first fixation duration was the duration of the first fixation on a stimulus, and gaze duration was based on the summed durations of all fixations on a word. For the gaze duration measure, saccade durations were excluded, because only minimal additional effects would be expected by including them (Rayner, 1998). Skipped items were also excluded from analysis. To increase data quality, the following exclusion criteria were defined separately for each participant: Items deviating more than $SD = 2.5$ from the mean of the corresponding category in number or duration of first fixation were not included in the analysis. Because of the exclusion of these outliers and the skipped items, statistical data for the categories contained 86–91% of the items.

The effect of syllable-frequency (high vs. low) and word-frequency (high vs. low) was examined using separate 2×2 ANOVAs for the three dependent measures. Again, both factors were treated as within-participant factors in analysis by participants (F_1). Effects that proved to be reliable in this analysis were then tested in an item analysis (F_2) with both factors being treated as between-item factors. The relevant means for the three measures are presented in Table 3.

3.2.1. Number of fixations

For this measure, neither the main effect of syllable-frequency, nor the main effect of word-frequency was reliable, $F_1 < 1.43$ and $F_1 < 1.78$, respectively. However, there was a significant syllable-frequency by word-frequency interaction, $F_1(1,10) = 20.77$; $MSE = .01$; $p < .001$ and $F_2(1,76) = 11.83$; $MSE = .04$; $p < .001$. As can be seen in Table 3, for high-frequency words, there was a tendency that words with a low-frequency first syllable are fixated about $M = .10$ more often than words with a high-frequency first syllable, $F_1(1,10) = 2.75$; $MSE = .02$; $p < .128$ and $F_2(1,38) = 2.90$; $MSE = .04$; $p < .097$. An inverse pattern was found for low-frequency words: Words with a low-frequency first syllable were fixated $M = .21$ less often than words with a high-frequency first syllable, $F_1(1,10) = 10.73$; $MSE = .03$; $p < .01$ and $F_2(1,38) = 9.46$; $MSE = .05$; $p < .01$.

3.2.2. First fixation duration

The relevant main effect of syllable-frequency was reliable, $F_1(1,10) = 15.88$; $MSE = 912$; $p < .01$ and $F_2(1,76) = 6.00$; $MSE = 4702$; $p < .017$, as well as the main effect of word-frequency, $F_1(1,10) = 22.15$; $MSE = 3171$; $p < .001$ and $F_2(1,76) = 25.14$; $MSE = 4702$; $p < .001$. Furthermore, there was a significant syllable-frequency by word-frequency interaction in both analysis: $F_1(1,10) = 13.28$; $MSE = 679$; $p < .01$ and $F_2(1,76) = 4.29$; $MSE = 4702$; $p < .05$. As can be seen in Table 3, for low-frequency words, there was an inhibitory effect of syllable-frequency: Words with an high-frequency first syllable were fixated about $M = 69$ ms longer than words with a low-frequency first syllable, $F_1(1,10) = 20.34$; $MSE = 1,139$; $p < .001$ and $F_2(1,38) = 8.42$; $MSE = 5710$; $p < .01$. However, such an effect was not found for high-frequency words, $F_1 < 1$.

3.2.3. Gaze duration

For this measure, the main effect of syllable-frequency, $F_1(1,10) = 18.95$; $MSE = 2514$; $p < .0014$ and $F_2(1,76) = 7.44$; $MSE = 11,616$; $p < .01$, as well as the main effect of word-frequency, $F_1(1,10) = 35.56$; $MSE = 3,956$; $p < .0001$ and $F_2(1,76) = 23.10$; $MSE = 11,616$; $p < .0001$ were reliable. Furthermore, there was a word-frequency by syllable-frequency interaction, $F_1(1,10) = 25.23$; $MSE = 1995$, $p < .001$ and $F_2(1,76) = 8.15$; $MSE = 11,616$; $p < .01$. As shown in Table 3, subsequent analysis proved the inhibitory effect of syllable-frequency in low-frequency words to be reliable: Words with a high-frequency first syllable were looked at $M = 130$ ms longer than words with low-frequency first syllable, $F_1(1,10) = 26.04$; $MSE = 3762$; $p < .001$ and $F_2(1,38) = 10.70$; $MSE = 16,922$; $p < .01$. In contrast, no effect of syllable-frequency was observed in high-frequency words, $F_1 < 1$.

3.3. Discussion

The aim of Experiment 2 (A) was to see whether an inhibitory effect of syllable-frequency could also be observed in the eye-movement pattern during a lexical decision task. The important finding was that such an inhibitory effect was observed in number of fixations, in the duration of the first fixation, and in gaze duration. For number of fixations, an inhibitory effect of syllable-

Table 3
Means (standard deviations) for eye-movement patterns during the lexical decision task in Experiment 2 (A): Number of fixations per word, mean duration of the first fixation, and gaze duration

	High word-F		Low word-F	
	High syllable-F	Low syllable-F	High syllable-F	Low syllable-F
Number of fixations	1.19 (.15)	1.29 (.17)	1.42 (.20)	1.20 (.18)
First fixation duration	265 (75)	258 (70)	374 (98)	309 (92)
Gaze duration	313 (87)	315 (85)	494 (117)	361 (109)

Note. Word-F, word-frequency; Syllable-F, syllable-frequency.

frequency was observed in low-frequency words: Words with a high-frequency first syllable were fixated more often than words with a low-frequency first syllable. In contrast, there was a trend towards a facilitative effect of first syllable-frequency for high-frequency words. This pattern of results is somewhat surprising for two reasons. First of all, the sensitivity of the measure number of fixations to the lexical characteristics of reading material (e.g., word-frequency) is still a matter of debate. Some research showed that the number of fixations exhibited during reading is modulated by word-frequency (Rayner, Sereno, & Raney, 1996; Sereno, 1992). These findings match with evidence showing that the perceptual span of a reader is not constant, but becomes smaller with increasing difficulty of the stimulus material: When fourth grade children read a reading-level appropriate text, their perceptual span was comparable to that of adults (Rayner, 1986). In contrast, other theoretical positions deny any influence of the lexical characteristics of stimulus material on number of fixations (e.g., O'Regan, 1990). Beyond the mere existence of an inhibitory effect of first syllable-frequency on number of fixations, it is also quite surprising that syllable-frequency had an inhibitory effect for low-frequency words, but a facilitative tendency for high-frequency words. However, a similar pattern of results was also reported by Perea and Carreiras (1995) for a perceptual identification task. The reason for this pattern of results might be that the inhibitory effect of syllable-frequency could possibly be reduced to an effect of syllable-neighborhood (Perea & Carreiras, 1998). According to this explanation, not the frequency of the syllable itself, but rather the number of higher-frequency syllabic neighbors (i.e., words that share the first syllable with the target word) would inhibit the processing of target words in lexical decision. However, in the present experiment, syllable-frequency was used as critical criterion. The fact that high-frequent words with high-frequent first syllables tend to have less or no higher-frequency syllabic neighbors than low-frequency words, might explain the absence of a syllable-frequency effect in high frequent words.

For first fixation duration, the observation of an inhibitory effect of syllable-frequency in low-frequency words is not so surprising. First fixation duration has been shown to reflect online language processing (Rayner et al., 1996; for a review, see Rayner, 1998). For example, longer first fixation durations are exhibited during the reading of low-frequency words than during the reading of high-frequency words, an effect that was also observed in the present experiment. It is thus likely that the inhibitory effect in low-frequency words reflects increased processing demands for high-frequency first syllables. Furthermore, it is of interest that first fixation duration is supposed to be especially sensitive to fast cognitive processes (Rayner & Pollatsek, 1987). In the case of low-frequency words, the average fixation duration on words with low-frequency first syllables was 300 ms. Sereno, Rayner, and Posner (1998) proposed that the oculomotor latency from initiation of an eye-movement motor program to the execution of a saccade is about 100 ms. Thus, syllable-frequency could affect processing somewhere prior to 200 ms after the beginning of reading a word.

The third measure, gaze duration, is a combined measure of number of fixations and duration of fixations and, given that it reflects the total processing time on a word, therefore is the measure that is most adequately compared to response times during a lexical decision task. It is noteworthy that the syllable-frequency effect of about 130 ms in gaze duration (in the case of low-frequency words) was large compared to that found in gaze duration for effects of neighborhood frequency. For example, Grainger, O'Regan, Jacobs, and Segui (1989) reported an effect of 52 ms and Perea and Pollatsek (1998) reported an effect of 39 ms in total processing time.

The important implication of Experiment 2 (A) is that eye movements are an appropriate measure to examine the effects of syllable-frequency. Especially gaze duration seems to be a sensitive measure that—comparable to response times during a lexical decision task—reflects the total processing time for a word.

4. Experiment 2 (B)

Experiment 2 (A) revealed that the inhibitory effect of (first) syllable-frequency on lexical decision times can also be observed in eye-movement parameters. Assuming that eye movements are a measure sensitive to syllable-frequency, the aim of Experiment 2 (B) was to examine the effect of syllable-frequency on eye movements during a naming task. As already mentioned, Perea and Carreiras (1998) proposed that during naming, syllable-frequency should have a facilitative effect on the construction of phonological output, but an inhibitory effect on lexical access. Whereas the facilitative effect on the construction of phonological output would obviously affect onset of articulation, this facilitation would not be expected to result in an effect on eye-movement parameters.

However, the recording of eye movements during naming poses methodological problems. If words are sounded out during reading, fixations tend to be more frequent and longer. Furthermore, readers tend to fixate words following those that they are still sounding out (Rayner, 1998). This phenomenon was interpreted by Lévy-Schoen (1981) stating that the eyes hold place on some words, in order to avoid that the voice would go too far ahead. Obviously, these random delays in eye movements could result in increased statistical noise, when occurring randomly on various words across all experimental categories. To avoid this problem, in the present experiment we mixed the pronounceable experimental stimuli (i.e., words) with non-pronounceable consonant strings (see below). This was done in a way such that every experimental stimulus was preceded by a consonant string. Because the consonant strings that preceded the critical stimuli could not be read aloud, we expected that participants should not precedingly fixate experimental stimuli, while waiting for articulation to catch up with eye movements. This task design is similar to the lexical naming task, in which participants are presented with words and pseudowords and are told to read an item aloud only if it is a word. This variant is known to provide an estimate of lexically based naming performance (Forster & Davis, 1991), which highly correlates with that during standard word naming tasks (Andrews & Heathcote, 2001). In contrast to the lexical naming task, in the present experiment, participants were presented with words and consonant strings and told to read items aloud only if they were pronounceable. This variant of the task does not necessarily require lexical retrieval, but only a check for pronounceability.

4.1. Method

4.1.1. Participants

The 12 participants (four male) in this experiment ranged in age from 20 to 45 years and were $M = 30$; 11 (years; months) old. All were German native speakers, had normal or corrected to normal vision and did not receive a reward for participation.

4.1.2. Apparatus

The same apparatus, experimental setting, and validation procedure of recording quality were used as in Experiment 2 (A). In the present experiment, poor recording quality and track loss led to the exclusion of one participant.

4.1.3. Design and stimulus material

The same 80 words as in Experiment 2 (A) were used as stimuli, resulting from the orthogonal combination of the factors word-frequency and syllable-frequency.

4.1.4. Task and procedure

To carry out the recording of eye movements during a naming task, the 80 experimental stimuli, the additional 80 consonant strings, and 80 filler items (which also were consonant strings) were presented to the participants. These 240 items were shown in lowercase letters with appropriate capitalization on seven screens in comma separated lists. Again, each screen consisted of 36 items in six lines (while the last screen contained only 24 items in four lines) and each line contained six items. Effects of line sweep on the experimental stimulus were again avoided by filler items in the first and last position of every line. Of the four remaining items per line, two were taken from the experimental stimuli and two were taken from the consonant strings. The experimental stimuli were placed in pseudo-random fashion so that they were always preceded by a consonant string.[3] Participants were instructed to search through the lists from left to right beginning with the first line. The task was to sound out loud only the words within the stimulus material, that is, participants had to perform a go/no-go naming task. For familiarization with the task, a training screen with two lines was presented prior to the task.

4.2. Results

Again, number of fixations, first fixation duration, and gaze duration were entered in the analysis. Exclusion of outliers was done using the same criteria used in Experiment 2 (A). This resulted in 77–88% of stimulus material of each category being submitted to statistical analysis. The effect of the factors syllable-frequency and word-frequency was analyzed by 2×2 ANOVAs separately for the three measures. The relevant means for number of fixations, first fixation duration, and gaze duration are presented in Table 4.

4.2.1. Number of fixations

The relevant main effect of syllable-frequency was reliable for number of fixations: As evident in Table 4, words with a high-frequency first syllable were fixated $M = .17$ more often than words with a low-frequency first syllable, $F_1(1,11) = 12.80$; $MSE = .02$; $p < .01$ and $F_2(1,76) = 9.74$; $MSE = .04$, $p < .01$. Furthermore, the main effect of word-frequency was reliable. Low-frequency words were fixated $M = .20$ more often than high-frequency words, $F_1(1,11) = 21.36$; $MSE = .02$; $p < .001$ and $F_2(1,76) = 19.95$; $MSE = .04$; $p < .0001$. The word-frequency by syllable-frequency interaction was not reliable, $F_1 < 1$.

[3] Again, to control for potential parafoveal-on-foveal effects, the familiarity of the initial letters and the length of the items following the experimental stimuli were analyzed. Obviously the overall bigram frequency of the initial two letters of the items following the experimental stimuli was close to zero since the consonant strings used consisted of combinations of consonants which never (or very seldom) appear in written language (e.g., KCRQPZ, VBXLCT). When bigram frequency was submitted to a 2×2 ANOVA (based on experimental stimuli) with the factors word-frequency (high vs. low) and syllable-frequency (high vs. low), neither the main effects nor the interaction were reliable, all Fs < 1.4. The mean letter length of the items *following* the experimental stimuli was close to identical (high word-frequency [WF]/high syllable-frequency [SF]: 5.90; high WF/low SF: 5.85; low WF/high SF: 5.90; low WF/low SF: 5.80).

Table 4
Means (standard deviations) for eye-movement patterns during the naming task in Experiment 2 (B), with number of fixations per word, mean duration of the first fixation, and gaze duration

	High word-F		Low word-F	
	High syllable-F	Low syllable-F	High syllable-F	Low syllable-F
Number of fixations	1.32 (.20)	1.15 (.14)	1.49 (.28)	1.37 (.24)
First fixation duration	190 (68)	192 (70)	244 (93)	212 (64)
Gaze duration	264 (81)	211 (67)	332 (90)	272 (73)

Note. Word-F, word-frequency; Syllable-F, syllable-frequency.

4.2.2. First fixation duration

For this measure, the critical main effect of syllable-frequency was reliable in the participant analysis, $F_1(1,11) = 7.57$; $MSE = 365$; $p < .01$, but was reduced to a tendency in the item analysis, $F_2(1,76) = 2.54$; $MSE = 1523$; $p < .12$. The main effect of word-frequency was reliable in both analyses, $F_1(1,11) = 9.26$; $MSE = 1758$; $p < .011$ and $F_2(1,76) = 13.89$; $MSE = 1523$; $p < .001$. There was no syllable-frequency by word-frequency interaction, $F_1 < 2.06$.

4.2.3. Gaze duration

As shown in Table 4, results show a clear-cut pattern for this measure. An inhibitory effect of syllable-frequency was reliable: Words with a high-frequency first syllable were fixated about $M = 47$ ms longer than words with a low-frequency first syllable, $F_1(1,11) = 46.64$; $MSE = 575$; $p < .0001$ and $F_2(1,76) = 13.97$; $MSE = 2936$; $p < .001$. Furthermore, there was a significant main effect of word-frequency, with high-frequency words being looked at about $M = 70$ ms shorter than low-frequency words, $F_1(1,11) = 21.08$; $MSE = 3092$; $p < .001$ and $F_2(1,76) = 33.72$; $MSE = 2936$; $p < .0001$. The syllable-frequency by word-frequency interaction was not reliable, $F_1 < 1.14$.

4.3. Discussion

An inhibitory effect of syllable-frequency was observed in *number of fixations* during the naming task. In contrast to the lexical decision task, this inhibitory effect of syllable-frequency was observed for both high- and low-frequency words. As concerns the duration of the first fixation, there was a tendency towards an inhibitory effect of syllable-frequency. However, more importantly, as concerns gaze duration (a measure reflecting the total processing time for a word) an inhibitory effect of syllable-frequency was found for both low- and high-frequency words.

This pattern of results is somewhat surprising when compared with the results of Carreiras and colleagues, but well in line with the expectations for eye-movement parameters during a naming task. The critical measure gaze duration revealed the same inhibitory effect of syllable-frequency for both high- and low-frequency words as duration of articulation did in Experiment 1. As mentioned above, it was assumed that during naming, syllable-frequency has an inhibitory effect on lexical access. However, we argued that for the measure onset of articulation, this inhibitory effect is masked by a facilitative effect of syllable-frequency on the construction of phonological output. Following this line of argument, it is not surprising that—despite a null effect on onset of articulation in Experiment 1—an inhibitory effect of syllable-frequency on gaze duration (which we assume to be affected by ease of lexical access, but not by ease of construction of phonological output) was found in Experiment 2 (B). Gaze duration therefore helped to disentangle the assumed differential effects of syllable-frequency on these two processes, i.e., an inhibitory effect on lexical access and a facilitative effect on the construction of phonological output—revealing an inhibitory effect of syllable-frequency on lexical access also during naming.

5. Reanalysis of Experiments 1, 2 (A), and 2 (B)

5.1. Correlations

In Experiments 1, 2 (A), and 2 (B) as well as in the lexical decision task in Conrad and Jacobs (2004) identical stimulus material was used. To check whether the same inhibitory effect of syllable-frequency occurred across these four tasks, a correlational analysis of item means was performed for the theoretically relevant measures articulation duration during naming (Experiment 1), gaze duration during lexical decision (Experiment 2 (A)), gaze duration during reading aloud (Experiment 2 (B)), and response times during lexical decision (Conrad & Jacobs, 2004). High correlations were found between response times during lexical decision and gaze duration during lexical decision, $r(80) = .60$, $p < .0001$, as well as for response times during lexical decision and gaze duration during reading aloud $r(80) = .60$, $p < .0001$. Furthermore, there was a high correlation between gaze duration during lexical decision and gaze duration during reading aloud: $r(80) = .54$, $p < .0001$. Concerning articulation duration during naming, there were reliable correlations with response times during lexical decision,

$r(80) = .29$, $p < .01$, and with gaze duration during reading aloud: $r(80) = .28$, $p < .012$. A correlation of borderline reliability was found between articulation duration during naming and gaze duration during lexical decision: $r(80) = .21$, $p < .07$.

5.2. Regression analysis

To investigate whether the syllable-frequency effect found in the three experiments of the present study could be explained in terms of higher-frequency syllabic neighbors (as it was the case for lexical decision in Perea & Carreiras, 1998), a regression analysis was conducted. The regression analysis with five predictors (log of word-frequency, log of syllable-frequency, number of higher-frequency syllabic neighbors, number of syllabic neighbors, and item length in letters) was performed on the theoretically relevant measures articulation duration during naming (Experiment 1), gaze duration during lexical decision (Experiment 2 (A)), and gaze duration during reading aloud (Experiment 2 (B)).

5.2.1. Experiment 1: Articulation duration

For the naming task in Experiment 1, a regression analysis was conducted for the measure duration of articulation. The model was significant: $F(3, 79) = 5.93$, $p < .001$, $R^2 = .19$, adj $R^2 = .16$. The regression analysis revealed an inhibitory effect of syllable-frequency, $t(79) = 2.48$, $p < .015$, $b = .26$, an effect of word-frequency, $t(79) = 2.92$, $p < .005$, $b = -.31$, and an inhibitory effect of letter length, $t(79) = 2.60$, $p < .011$, $b = .27$.

5.2.2. Experiment 2 (A): Gaze duration

For the gaze duration measure during the lexical decision task in Experiment 2 (A) the model was significant: $F(4, 79) = 11.10$, $p < .0001$, $R^2 = .372$, adj $R^2 = .34$. The regression analysis revealed an inhibitory effect of syllable-frequency, $t(79) = 2.32$, $p < .023$, $b = .35$, an inhibitory effect of number of higher-frequency syllabic neighbors $t(79) = 3.05$, $p < .003$, $b = .37$, an effect of number of syllabic neighbors $t(79) = 1.88$, $p = .06$, $b = -.28$, and an effect of word-frequency $t(79) = 2.75$, $p < .007$, $b = -.31$.[4]

[4] Henderson and Ferreira (1990) provided evidence that less parafoveal information is acquired if the frequency of the foveal stimulus is low (foveal-on-parafoveal effect). That is, gaze duration on an experimental stimulus is longer, if the item preceding the stimulus is of low frequency than if it is of high frequency. In Experiment 2 (A) experimental stimuli were preceded by both, words and pseudowords—to examine, whether the effects of syllable-frequency found in Experiment 2 (A) could be explained in terms of foveal-on-parafoveal effects, we added lexicality (word vs. pseudoword) of the items preceding the experimental stimuli as predictor to an additional multiple regression analysis. Results revealed that lexicality was a reliable predictor of gaze duration; however, the reliability of the other predictors (e.g., syllable-frequency) did not get weaker but stronger.

5.2.3. Experiment 2 (B): Gaze duration

The model was significant for the measure gaze duration during reading aloud in Experiment 2 (B), $F(3, 79) = 14.91$, $p < .0001$, $R^2 = .37$, adj $R^2 = .35$. The regression analysis revealed an inhibitory effect of syllable-frequency, $t(79) = 3.39$, $p < .001$, $b = .31$, an effect of word-frequency, $t(79) = 6.13$, $p < .0001$, $b = -.57$, and an inhibitory effect of letter length, $t(79) = 1.68$, $p < .10$, $b = .15$.

6. General discussion

The goal of the present study was to examine the effects of syllable-frequency during naming and lexical decision using eye-movement recordings to improve the comparability of performance in both tasks. Whereas the inhibitory nature of the syllable-frequency effect on lexical access had already been well documented for lexical decision and perceptual identification tasks, the available empirical evidence was contradictory for naming tasks. The important finding of the present study, made possible by the use of eye-movement recordings, is that inhibitory effects of syllable-frequency could also be observed in naming.

Assessments and the reanalysis (in terms of a regression analysis) of an additional measure, articulation duration, in Experiment 1 suggested the existence of an inhibitory effect of syllable-frequency also during naming. As concerns eye-movement parameters, an inhibitory effect of syllable-frequency was observable, no matter whether participants had to perform a lexical decision or a naming task: Experiment 2 (A) revealed that during lexical decision the inhibitory effects of high first syllable-frequency and of number of higher-frequent syllabic neighbors could be observed in gaze duration. In part, these findings match with those of Perea and Carreiras (1998) who found that the inhibitory effects during lexical decision were due to the number of higher-frequency syllabic neighbors. However, in contrast to our results, the authors showed that the effect of syllable-frequency was negligible. Experiment 2 (B) (and the corresponding reanalysis) replicated the inhibitory effect of syllable-frequency on gaze duration during a naming task. No effect of higher-frequency syllabic neighbors was found.

These findings suggest that the measurement of onset of articulation (i.e., naming latency), the only dependent variable used by previous studies on effects of syllable-frequency in reading aloud, does not necessarily provide sufficient information about the processes underlying the naming of polysyllabic words. Previous studies tended to conclude that an observed facilitation of naming latencies showed that the word processing time disadvantage through higher first syllable-frequency was task-dependent. However, the present study strengthens the basis of empirical findings suggesting that syllabic units are automatically processed when polysyllabic words are read for two reasons. First, effects of the properties of syllabic structure emerged in an aspect of human behavior that is more closely connected to the natural process of reading than response times during lexical decision: Eye movements. Second, the inhibitory effect of syllable-frequency cannot simply be attributed to task-specific processes that would only be relevant in lexical decision or perceptual identification. The results of Experiments 2 (A) and (B) and the high correlation on item level for gaze duration between these two eye-movement recordings suggest that the same processes sensitive to syllable-frequency in lexical decision also take place when the task consists in naming a word.[5]

6.1. The differential effect of syllable-frequency on two processes during naming

Perea and Carreiras (1998) mentioned that a differential effect of syllable-frequency could be the reason for the facilitative effect of syllable-frequency during naming: For onset of articulation (naming latency), the facilitation of the production of phonological output could mask the inhibitory effect of syllable-frequency on lexical access. Perea and Carreiras (1998) argued that during pseudoword naming (in contrast to word naming) a strong and consistent facilitative effect of syllable-frequency can be observed. Obviously, for the naming of pseudowords, lexical access is not mandatory (if not impossible) and only the expected facilitative effect of highly overlearned processing units (i.e., first syllables of high frequency) on production of phonological output takes effect (Carreiras & Perea; 2004). On the basis of these findings, we explained the fact that in our Experiment 1, an inhibitory effect of syllable-frequency on lexical access during naming could only be observed in duration of articulation, but not in onset of articulation, as a consequence of this differential effect of syllable-frequency on lexical access and construction of phonological output. However, because of this differential effect on two distinct processes involved in naming, we argue that the measure onset of articulation is insufficient for strongly constraining accounts of syllable-frequency effects during naming.

Using eye movements as an additional dependent measure in Experiments 2 (A) and 2 (B), provided two advantages compared to the measures onset and duration of articulation used in Experiment 1. First of all, eye movements were expected not to be affected by processes of construction of phonological output and therefore allowed to disentangle the assumed inhibitory effect of lexical access and the facilitative effect of construction of phonological output. Furthermore, eye-movement parameters could be obtained for both the naming and the lexical decision task, and therefore provided the possibility to directly compare the effects of syllable-frequency using one measure of total processing time: Gaze duration. Disentangling the processes of lexical access and construction of phonological output in Experiment 2 (B) supported this line of argumentation. All three eye-movement parameters showed an inhibitory effect of syllable-frequency during naming. These findings strongly support Perea and Carreiras' hypothesis (1998) of a differential effect of syllable-frequency on lexical access and the construction of phonological output: The naming latency advantage of words with high frequent first syllables can be understood as resulting from a trade-off between the described relative disadvantage in lexical access and a clear, even stronger advantage for producing the phonology of familiar syllables.

6.2. A task independent inhibitory effect of syllable-frequency on lexical access: A challenge for computational models of word recognition

A theoretically relevant conclusion of the present study is that high, first syllable-frequency hindered lexical access in a way that is not task-dependent: During naming as well as lexical decision, an inhibitory effect of syllable-frequency on lexical access could be observed. This finding constrains future computational models of polysyllabic word recognition. Currently, only a single computational model of naming provides the necessary prerequisite to possibly account for the present findings by simulation. In contrast to other successful computational models of (monosyllabic) word recognition, such as the Multiple Read-Out Model (MROM, Grainger & Jacobs, 1996; Jacobs et al., 2003), the revised Dual-Route Cascaded model (DRC, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), or the revised Activation-Verification model (AVM, Paap, Chun, & Vonnahme, 1999), syllabic processing units are only implemented in the multiple-trace memory (MTM) model for polysyllabic word reading (Ans, Carbonnel, & Valdois, 1998).

The MTM is a feedforward model, composed of four layers of processing units, an orthographic input layer, a second orthographic layer, an intermediate episodic memory (EM) layer, and a phonological output layer. Each unit of the orthographic input layer is connected to each EM unit, each EM unit is connected to each unit of the phonological output layer and also to each unit of the second orthographic layer. Furthermore, two reading mode (RM) units send activation to all EM units. By means of these two reading mode units, two distinct

[5] Although in Experiment 2 (A) a decision upon the lexicality of the stimuli and in Experiment 2 (B) the naming of the stimulus material was required, the go/no-go component of both tasks could restrict the generalizability of the results.

reading mechanisms are implemented: Global reading (coding information about whole words) and analytic reading (coding information about word segments, most often syllables). The global or the analytic reading mechanisms are activated by applying a two component vector to the two RM units, either G = [1 0] or A = [0 1], respectively.

Although syllabic units of representation are implemented in the MTM, procedural and architectural constraints question a successful prediction of the inhibitory syllable-frequency effect. First of all, the two distinct reading mechanisms implemented in the MTM are not applied in parallel (as, for example, in the DRC). Letter strings presented to the MTM are always processed in the global reading mode first, thus applying knowledge about the whole word only and excluding syllable-specific knowledge. Only if the global reading procedure fails, the letter string is processed syllable per syllable in the analytic reading mode.[6] Since most words (97.52%) are processed in the global reading mode and only very low-frequency words and pseudowords are processed in the analytic reading mode, the MTM in its' present form cannot predict the inhibitory effect of syllable-frequency (which in the present paper was found during the naming of high- and low-frequency words). One can speculate: whether the influence of syllabic segment traces in the EM could also be introduced in the global reading mode. The RM units could be activated by a vector $[1\ x]$, with $0 < x \leqslant 1$, allowing an activation not only of EM word traces but also (to some degree) the activation of EM segment traces corresponding to the first syllable of a word.[7]

However, even if the constraint of the exclusive application of the global or the analytic reading mode could be overcome by a successful activation of syllabic EM segment traces during global reading, the strict feedforward architecture of the MTM is still a drawback for the prediction of the inhibitory effect of syllable-frequency on processing times. Before depicting these architectural constraints in more detail, it might be helpful to (verbally) account for the inhibitory syllable-frequency effect—in a way analogous to Grainger and colleagues' account of the orthographic neighborhood frequency effect (Grainger & Jacobs, 1996; Grainger et al., 1989; see also Carreiras et al., 1993; Carreiras & Perea, 2002). During the processing of a polysyllabic word, sublexical, syllabic processing units could be activated via lower levels and, in turn, could activate all entries in the mental lexicon that share an identified syllable in a specific position with the input. The size of this cohort of competing candidates, the syllabic neighbors, depends on syllable-frequency. In particular, a word's higher-frequent syllabic neighbors would, by the mechanism of lateral inhibition, interfere with the processing of a target word and thus cause the experimentally observed delays in recognition latencies for words with an high-frequent first syllable.

Such a (or a similar) account cannot be realized in the MTM in its present form. During training (i.e., as long as a word cannot be read globally) EM word traces and EM segment traces are created—both types of traces accumulate within the EM layer. To realize the activation of a cohort of syllabic neighbors by the first syllable of a presented letter string, it would be necessary that the macro word units (consisting of the subset of EM units responding to a specific word) in the EM layer would be interconnected with the macro segment units (consisting of the subset of EM units responding to a specific segment, in this case a syllable) in the EM layer. This could be realized by strengthening the connections between the active macro word units and the active macro syllabic units during the learning of a word (until a word can be read globally, it is presented in both, global and analytical mode). By means of these syllable-word interconnections, the syllabic macro units corresponding to the first syllable of a given letter string could activate the syllabic neighbors (i.e., macro word units) of the given letter string.[8] Furthermore, to introduce lateral inhibition of syllabic neighbors on the target word, it would be necessary to introduce inhibitory connections between the macro units for different words in the EM layer.

In any case, the challenge is great for any computational model to simulate inhibitory and facilitative influences at different levels of processing that generate inhibitory effects on response times measured in lexical decision and perceptual identification tasks and on

[6] To be more specific, the syllable is the default size of processing in the analytic mode. However, if the processing of a syllable fails because syllabic units are unusual (but existing) or non-existing (but pronounceable), a more fine grained orthographic analysis on the basis of graphemes is applied.

[7] In the global reading mode, the focal window covers the whole letter string presented and the focalization point (i.e., the 0 cluster) is located at the rightmost letter of the first orthographic vocalic grapheme in this focal window—corresponding to the rightmost letter of the orthographic vocalic grapheme of the first syllable. During analytic reading, the focalization point is also positioned at the rightmost letter of the orthographic vocalic grapheme of the syllable actually being processed. Furthermore, during learning in the analytic mode, the phonological echo of a syllable (regardless of its' position within a word) is always presented to the clusters belonging to the first syllabic subset of the phonological layer. Therefore, analytic processing during global reading would only take the first syllable into account.

[8] Since during analytic reading orthographic word segments are always considered in their orthographic context (as Ans et al., 1998, state, *cho* in *chocolate* and *cho* in *chorale* are two distinct orthographic segments) the activation of syllabic neighbors due to their shared first syllable could only be realized if no right contextual characters of the first syllable are considered (by setting the context size parameter to $cs = 0$).

articulation duration and eye-movement parameters in naming tasks, as well as facilitative effects on naming latencies. A promising for future research is the differential influence of syllable-frequency and the number of higher-frequency syllabic neighbors during naming and lexical decision tasks.

Appendix A

Stimulus material and item means for the theoretically relevant measures in Experiments 1, 2 (A), and 2 (B).

	Experiment 1 Naming[a] Articulation duration	Experiment 2 (A) Lexical decision[b] Gaze duration	Experiment 2 (B) Naming[c] Gaze duration
High word-F, high syllable-F			
ANDERS	380	313	278
ANFANG	429	183	295
AUFBAU	453	242	244
BEGINN	348	429	298
BEREIT	418	240	288
BESUCH	364	282	191
BEVOR	481	302	243
BEZIRK	389	349	236
EINIG	350	315	300
ERFOLG	449	324	268
GEBIET	420	460	256
GENAU	430	276	247
GESAMT	389	333	207
GESETZ	417	324	315
GEWALT	424	408	169
MITTE	391	245	205
RECHEN	392	414	285
SOGAR	439	258	224
UMSATZ	482	362	224
VORHER	446	305	262
High word-F, low syllable-F			
DIREKT	372	324	323
DOLLAR	343	207	140
FAHREN	398	284	250
GRENZE	429	344	256
HANDEL	374	254	222
HELFEN	288	255	208
HILFE	334	258	136
HOTEL	423	377	240
KIRCHE	407	333	187
KOSTEN	366	305	238
LEHRER	447	248	229
MONTAG	479	469	180
MUSIK	343	352	233
PARIS	352	376	155
PARTEI	440	258	191
PERSON	419	329	244
RUHIG	429	440	260
SYSTEM	426	506	205
WARUM	338	353	210
ZIMMER	405	153	182
Low word-F, high syllable-F			
ADELN	371	528	309
ALSTER	465	456	373
ALTERS	469	698	429
ANBEI	531	370	313
ANHAND	363	395	308
ANTUN	496	467	282
AUFTUN	483	438	352
BESAGT	485	440	291
EINHER	518	493	408
ERBEN	383	546	462
ERDIG	392	342	273
ERDUNG	381	593	212
GEDEIH	469	655	347
GESELL	469	724	347
MITHIN	414	396	360
UMHIN	364	668	307
UNWEIT	465	391	298
VORDEM	415	687	428
WIRBEL	459	315	207
WIRTIN	412	456	298
Low word-F, low syllable-F			
ACHSEL	443	592	311
BAGGER	379	364	267
DIPLOM	393	265	224
ELSTER	473	514	238
EXTERN	434	287	282
EXTRA	394	222	188
FAHRIG	422	700	389
FASELN	468	462	382
GEISEL	468	348	231
GEIZIG	514	256	287
GLATZE	405	230	352
HARZIG	396	418	362
HECKE	338	280	257
MENSA	399	485	228
MUSKEL	424	342	215
PILGER	385	455	229
PINSEL	414	238	306
TADELN	420	369	249
TIGER	372	310	318
ZIRKUS	472	229	220

Note. Word-F, word-frequency; Syllable-F, syllable-frequency. Item means based on [a]18, [b]11, and [c]12 participants.

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