

Timing in Sentence Production

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Recently, a new theory of timing in sentence production has been proposed by Ferreira (1993). This theory assumes that at the phonological level, each syllable of an utterance is assigned one or more abstract timing units depending on its position in the prosodic structure. The number of timing units associated with a syllable determines the time interval between its onset and the onset of the next syllable. An interesting prediction from the theory, which was confirmed in Ferreira's experiments with speakers of American English, is that the time intervals between syllable onsets should only depend on the syllables' positions in the prosodic structure, but not on their segmental content. However, in the present experiments, which were carried out in Dutch, the intervals between syllable onsets were consistently longer for phonetically long syllables than for short syllables. The implications of this result for models of timing in sentence production are discussed. © 1994 Academic Press, Inc.

The present paper concerns the timing of sentences in language production, i.e., the question of how word durations and the locations and durations of pauses in spoken sentences are determined. Many models of language production assume that the articulation of an utterance is preceded by two discrete sets of processes. These are, first, conceptual processes resulting in a representation of the content of the utterance, and, second, the linguistic formulation of the utterance resulting in internal or overt speech (see, for instance, Levelt, 1989). The temporal structure of utterances is affected by both types of processes. In addition, there are physiological constraints on speech timing. Speakers must, for instance, pause from time to time to breathe, and articulatory movements take a certain minimal time to execute (e.g., Klatt, 1973, 1976).

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Examples of timing effects arising at the conceptual level are variations in speech rate due to different emotional states, the occurrence of pauses due to the speaker's need to think about the continuation of the utterance, and the insertion of pauses for rhetorical purposes (e.g., Clemmer, O'Connell, & Wayne, 1979; Drommel, 1980; Goldman-Eisler, 1968; Hawkins, 1972; O'Connell & Kowall, 1983; Williams & Stevens, 1972). Conceptual effects, interesting as they may be, will not be considered here.

Instead, this article focuses on timing effects arising during the linguistic formulation of sentences. As will be shown below, the timing of a sentence is affected by phonological properties of its words and by properties of its syntactic structure. These effects can, of course, be traced back to conceptual determinants because the choice of words and syntactic structure depends on the message to be expressed. However, the temporal regularities at issue here can only arise after words have been selected and sentence structures have been built, and must, therefore, originate during the linguistic formulation of the utterance.

For a number of languages phoneticians have mapped out in great detail the conse-

quences of various properties of word forms for spoken word durations. The durations of English words tend to increase with the number of syllables they include, but this increase is not linear for two reasons. First, there are compression effects; i.e., the durations of stressed syllables tend to decrease as the number of syllables following in the same word increases. Second, syllables vary in duration depending on their segmental composition. Syllables with many segments are typically longer than syllables with fewer segments, though again compression effects have been observed in some studies. Syllable durations also depend on the nature of their constituent segments. Segment types vary in mean duration (e.g., English tense vowels are, on average, longer than lax vowels, and voiceless fricatives are longer than voiced ones), and the duration of segments are often modified by phonetic features of their neighbors. Vowels, for instance, tend to be longer before voiced than before voiceless consonants. Finally, stressed syllables are usually longer than unstressed ones (e.g., Crystal & House, 1988a, 1988b, 1988c, 1988d, 1988e, 1990; House & Fairbanks, 1953; Klatt, 1973, 1975, 1976; Luce & Charles-Luce, 1985; Nakatani, O'Connor, & Aston, 1981; Oller, 1973; Peterson & Lehiste, 1960; Umeda, 1975).

There is also ample evidence showing effects of sentence structure on speech timing. A well-known phenomenon is final lengthening, i.e., the fact that a given syllable is usually longer when it appears at the end of a major syntactic constituent than when it appears constituent-internally (Cooper, 1976; Cooper & Paccia-Cooper, 1980; Klatt 1975, 1976; Oller, 1973; Umeda, 1975). In addition, utterance-final syllables have sometimes been found to be lengthened more than utterance-internal phrase-final syllables (e.g., Cooper & Danly, 1981; Lehiste, 1973). Often, final lengthening is accompanied by a pause at the constituent boundary (e.g., Cooper & Paccia-Cooper, 1980; Klatt, 1976; Klouda & Cooper, 1987).

Thus, the duration of a word depends both on the number and types of syllables and segments it includes and on its position in the sentence. Concerning the question of how lexical and syntactic information is integrated, two opposing views have been proposed. On one, hereafter called the direct view, syntax directly affects phonetic form, whereas on the other, dubbed the indirect view, syntax affects phonetic form via a mediating prosodic representation.

Direct models predict temporal properties of utterances, such as syllable or word durations or the probability of final lengthening and pauses, on the basis of lexical factors and characteristics of the syntactic surface structure. For instance, in Cooper and Paccia-Cooper's (1980) model, the probability of final lengthening of a word and the duration of the following pause are functions of an index of boundary strength, which is based on the position of the word in the syntactic structure, the number of content words in each major syntactic constituent, and the distance of the word from the so-called bisection point, which is a point approximately in the middle of the utterance (for other direct models see Grosjean, Grosjean, & Lane 1979; Kaisse, 1985; Klatt, 1976; Lindblom & Rapp, 1973).

On indirect models, syntax affects the phonetic representation indirectly, via an intervening prosodic representation (e.g., Ferreira, 1993; Gee & Grosjean, 1983; Selkirk, 1986). This representation is part of the phonological representation of the utterance and consists of prosodic constituents, such as intonational phrases, phonological phrases, phonological words, and syllables. The prosodic constituents of a sentence are derived from its lexical words and syntactic surface structure (see Hayes, 1984; Nespor & Vogel, 1986; Selkirk, 1984, 1986). For instance, phonological words can be defined by the right edges of major category words (i.e., nouns, adjectives, prepositions, and verbs). Thus, each phonological word comprises a major category word plus any preceding function words

(e.g., Selkirk, 1986; but see Nespor & Vogel, 1986). Phonological phrases correspond to major syntactic constituents. For instance, in the sentence *The young man from Holland brought his own bike to America*, the three constituents *The young man from Holland*, *brought his own bike*, and *to America* correspond to phonological phrases, whereas other syntactic constituents (e.g., *young man*, *his own bike*) do not correspond to phonological phrases (see Selkirk, 1986). Thus, though the phonological phrase structure of a sentence is derived from its syntactic phrase structure, the two structures are not necessarily identical. An intonational phrase comprises one or more phonological phrases and tends to correspond to a meaning unit. In declarative sentences, each intonational phrase is marked by a single falling pitch contour.

Direct and indirect models differ in their assumptions about the immediate determinants of final lengthening (for other differences see, for instance, Inkelas & Zec, 1990). According to direct models, the length of a word depends on its position in the syntactic structure, whereas according to indirect models, it depends on its position in the prosodic structure. Empirical evidence that is more consistent with an indirect model comes from a recent study by Ferreira (1993; see also Ferreira, 1991). Her subjects produced sentences in which target words appeared at the end of noun phrases, all of which corresponded to a single phonological phrase, but differed in syntactic complexity (e.g., *The friendliest cop* (low syntactic complexity) vs. *The friend of the cop* (medium complexity) vs. *The man who is a cop* (high complexity)). According to direct models (e.g., Cooper & Paccia-Cooper, 1980), the duration of the target (*cop* in the example) and the following pause should increase with increasing syntactic complexity. In contrast, indirect models do not predict such effects, as the position of the target in the phonological phrase structure is the same in all conditions. Indeed, no systematic syntactic com-

plexity effect was obtained for target or pause durations. When the target appeared phrase-internally (as in *The cop who is a friend*), its duration and the duration of the following pause were shorter than when it appeared phrase-finally, as predicted by both types of models.

The assumption of a prosodic representation that mediates between the syntactic and the phonetic representation is, of course, not sufficient to predict how long words and pauses will be. Additional assumptions are necessary to specify the phonetic consequences of different prosodic structures. Ferreira's (1993) paper mentioned above includes an interesting proposal concerning this issue. At the phonological level, Ferreira represents the rhythmic structure of an utterance as a metrical grid (see also Halle & Vergnaud, 1987; Liberman & Prince, 1977; Prince, 1983; Selkirk, 1984).¹ This is a two-dimensional representation consisting of metrical beats (see (1)). The vertical dimension of the grid encodes the prominence pattern of the utterance. The higher the stress level a syllable attains (i.e., the higher its column of beats) the more prominent it is. The rules determining stress levels are not relevant for the present purposes. On the horizontal dimension, each beat represents an abstract timing unit. In Ferreira's theory, each syllable is automatically associated with one beat. To capture constituent-final lengthening, an extra beat is inserted at the right edge of each prosodic constituent. In (1), for instance, two extra beats are inserted following the beat corresponding to *girls* to mark the ends of a phonological word and a phonological phrase, and four beats are inserted at the end of the utterance to mark the ends of a phonological word, a phonological phrase, an intonational phrase, and an utterance.

¹ It should be noted that Ferreira's grid construction rules differ substantially from those proposed elsewhere (e.g., Prince, 1983; Selkirk, 1984). However, these differences are not relevant to the present purposes.

(1)		x
		x
	x	x
	x	x
	x	x
x	x	x
x	xxx	xxxxx
The	girls	left

Ferreira’s model of timing has two parts. The first part describes how the time intervals between successive syllable onsets (called *slots* hereafter) are derived. Ferreira proposes that at the phonetic level each beat of the horizontal axis of the metrical grid should, at a given speech rate, correspond to a fixed time period. The more beats there are inserted at a particular location, the longer the time period should be from the onset of the preceding to the onset of the next syllable. The second part of the model is a quantitative model specifying how slots are divided into syllable and pause durations. Each syllable has a certain minimal duration, which depends on the number and types of segments it comprises. The actual duration of a syllable in a particular sentence position is its minimal duration plus a certain amount of lengthening, which is a fixed proportion of the duration of its slot. If a syllable does not fill its entire slot (because its minimal duration is relatively short and/or the slot is very long), a pause is inserted. As Ferreira shows, this model accurately predicts syllable and pause durations in different positions in the prosodic structure.

The first part of Ferreira’s model implies that slots, i.e., the time intervals between successive syllable onsets, are independent of the segmental content of the utterance. The phonetic evidence cited earlier shows that syllables vary greatly in length, depending on how many and which segments they include; yet the model makes the counterintuitive prediction that when they appear in the same position in the prosodic structure, their slots should all be equal. Relatively long syllables should be followed

by shorter pauses than short syllables, resulting in equal slots for all syllables. In support of this hypothesis Ferreira reports the results of an experiment in which subjects produced sentences including phonetically long or short target words (e.g., *green* or *black*) in phrase-medial or phrase-final position (see (2)).

- (2a) The table that I thought was *black* tempted me.
- (2b) The table that I thought was *green* tempted me.
- (2c) The *black* table tempted me.
- (2d) The *green* table tempted me.

As expected, targets and the pauses following them were longer in phrase-final position (2a,b) than in phrase-medial position (2c,d), and in each position phonetically long targets were longer than short ones (mean durations: 278 and 246 ms, respectively). Most importantly, pauses were longer following phonetically short than long targets, and the total duration of target plus pause was almost identical for long and short targets (312 and 314 ms, respectively). This result was replicated in a second experiment, in which phonetically long and short targets were pronounced either in a neutral manner or with contrastive prominence. Short targets were shorter than long ones, and both were longer in the prominent than in the nonprominent condition. Crucially, in both prominence conditions short targets were followed by longer pauses than long targets, again yielding slots of almost equal length for both target types.

Ferreira’s findings are important for a number of reasons. First, they support the assumption that a metrical grid mediates between the syntactic surface structure and the phonetic representation of an utterance. Second, they suggest that the structure of the metrical grid is independent of the segmental content of the utterance. Thus, the results are compatible with the linguistically motivated hypothesis that segmental and metrical information is captured in sep-

arate tiers of the phonological representation (e.g., Durand, 1990; Goldsmith, 1989; van der Hulst & Smith, 1982) and with Levelt's (1989) proposal that the metrical and segmental representations of an utterance are generated independently of each other. Third, the study provides evidence about the phonetic consequences of metrical and segmental information: Apparently, the time periods between successive syllable onsets are exclusively determined by metrical information (i.e., by the number of beats associated with each syllable), whereas segmental information is only relevant for the division of slots into syllable and pause durations. Thus, in the speech signal, the distribution of beats, which expresses the prosodic constituent structure of the utterance, is represented in the time periods between syllable onsets. Finally, the data imply that there is a process involved in the generation of utterance forms that governs the time intervals between syllable onsets and that is sensitive only to metrical, but not to segmental, information.

It is important to realize that the data do not permit one to say much about the nature of this process. In Ferreira's model, slots are computed first and are subsequently divided into syllable and pause durations. Ferreira demonstrates that the model accurately predicts syllable and pause durations obtained under various conditions. However, this does not mean that speakers necessarily have to carry out the corresponding computations. An important issue in current theories of speech motor control is whether temporal characteristics of speech, such as syllable and pause durations, are controlled directly, or whether they result from control of other parameters, such as the amplitude or velocity of speech gestures (e.g., Edwards & Beckman, 1988; Kelso, Saltzman, & Tuller, 1986; Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985; Ostry & Munhall, 1985; for an overview of theories of speech motor control see Levelt, 1989). Ferreira's results

show that metrical information is relevant for the determination of the time intervals between successive syllable onsets, but they do not reveal how this information is used: whether it plays a role in the computation of certain time intervals or in the control of certain articulatory parameters.

Even though it is still unknown which processes are affected by metrical information, Ferreira's finding that the intervals between syllable onsets solely depend on metrical information is intriguing and very important for the reasons given above. Therefore, it seemed appropriate to attempt to replicate this result in an independent study. This was done in the experiments reported below.

These experiments were carried out in Dutch. This language was chosen for practical reasons, not because it was expected to differ fundamentally in its timing from American English. Though Dutch and English phonology differ in many ways (e.g., in the phonemic inventories, syllabification rules, and frequencies of different syllable types), there are no obvious reasons why slots should be independent of the segmental content of the syllables filling them in one of the two languages, but not in the other. Nevertheless, it is entirely possible that the languages are different in this respect, and the present experiments should reveal whether or not this is the case.

For Experiment 1, 18 pairs of sentences, such as *De groene boon/bon kleeft aan het bord* [The green bean/ticket sticks to the plate], were created that differed only in one monosyllabic target word. The two targets differed in vowel length and therefore in duration. In the above example, the target *boon* has a long, and the target *bon* has a short vowel. The experiment included three test blocks. In each block, each subject produced both members of each sentence pair and 36 filler sentences. To prevent subjects from putting contrastive stress on the targets, the two members of an experimental pair were separated by at

least eight other sentences. The sentences were elicited using a procedure introduced by Ferreira (1991, 1993). Subjects were told that they should learn sentences so that they could reproduce them from memory. On each trial, one sentence was presented on a computer screen. As soon as the subjects thought that they knew the sentence, they pressed a button, thereby erasing the sentence. A little later, a response signal was presented. The subjects then recited the last sentence that had been shown. The durations of the target and the following pause were measured. As in Ferreira's study, a slot was defined as the sum of these two durations.

Across Experiments 1 through 5, differences in target length were introduced in different ways, namely by varying the length of the vowel, of the coda (i.e., the consonantal part of the syllable following the vowel), or the onset (i.e., the consonantal part of the syllable preceding the vowel). Ferreira's model predicts that regardless of how differences in target length are introduced, the slots for long and short syllables should always be equal. However, compensation was only obtained when the vowel or the coda, but not when the onset of the targets, was varied. Whereas Experiments 1 through 5 tested whether pause durations were affected by the segmental content of the *preceding* syllable, Experiment 6 tested whether they depended on the segmental content of the *following* syllable. Ferreira's model does not predict such a right-context effect on pause durations, because a pause shares a slot with the preceding, not the following, syllable. However, contrary to the prediction, a right-context effect was obtained in the experiment.

The next section describes the method used in all experiments and summarizes a number of minor results. In the following sections, the target words and the main results are described separately for each experiment. Under General Discussion, the implications of the findings for models of timing in sentence production are considered.

METHOD

Subjects

Each experiment was carried out with a different group of eight paid subjects. The subjects were undergraduate students of Nijmegen University and native speakers of Dutch. About two thirds of them were women.

Materials

Six experiments were run. The number of experimental sentence pairs in each experiment varied between 13 and 18, depending on how many suitable pairs could be found. In addition, the materials of each experiment included as many filler sentence pairs as experimental sentence pairs and six practice sentences. Each subject produced each member of each experimental and filler pair and each practice sentence three times (see below).

All sentences were similar in structure. Each included a nominal phrase and a verb phrase. The nominal phrase always consisted of a determiner, an adjective, and a noun (e.g., *De rijke broer* [the rich brother]). The sentences differed in the structure of the verb phrase. In some sentences, the verb was combined with an adjunct (as in *koelt snel af* [cools down **quickly**]), in others with a nominal phrase (as in *ergert de luisteraar* [annoys the **listener**]), a prepositional phrase (as in *komt uit Italië* [comes **from Italy**]), or an adverbial phrase (as in *klinkt nogal hol* [sounds **rather hollow**]).

The two members of a sentence pair had the same syntactic structure; they only differed in one content word, the target. In Experiments 1 through 5, the target word in the experimental sentences was the noun of the first noun phrase, and in Experiment 6 it was the verb. All targets were monosyllabic. The two targets of a pair varied systematically in phonetic length and are called the *long* and *short* target hereafter. How the targets differed across the experi-

ments will be described below (see Appendix for a listing of the experimental sentences).

The two members of a filler sentence pair differed on their last word. Two phonologically unrelated words were selected that were about equally plausible in the sentence context. Examples are *De oude man eet een groot stuk vis/vlees* [The old man eats a large piece of fish/meat] and *De kwade buurman roept zijn zoon/dochter* [The angry neighbor calls his son/daughter]. The fillers were included to divert the subjects' attention from the phonological relationship between the targets of the experimental sentence pairs. The practice materials consisted of six unrelated sentences.

Three sentence lists were constructed, differing only in the order of the sentences. Each list included the practice sentences and both members of each sentence pair. The lists began with the practice sentences, appearing in a different order in each list, followed by the experimental and filler sentences. At least eight sentences intervened between the two members of an experimental sentence pair. The order of testing sentences with long and short targets was counterbalanced such that within each list half of the sentences, selected at random, were tested first with long and then with short targets, and the others first with short and then with long targets. Otherwise the order of the sentences was random and different for each list.

Procedure

Subjects were tested individually. They were seated in a quiet room in front of a computer screen and a microphone. First, they read the instructions printed on a sheet of paper. According to the instructions, the goal of the experiment was to test how much time was necessary to memorize sentences. Subjects were told that they would see a series of sentences, which they should study until they knew them by heart, and that their study time and accuracy of recall would be measured.

After the subject had read the instructions, the first test block began, in which the first list of sentences was tested. At the beginning of each trial, the phrase *volgende zin* [next sentence] appeared on the screen. As soon as the subject pressed a button of a one-button panel, the screen was cleared, and 500 ms later a sentence was shown. It remained visible until the subject pressed the button again. The screen remained empty for 2 s, after which the question *wat gebeurt er?* [what happens?] was presented. Then the subject recited the last sentence that had been shown. Five seconds after speech onset, the next trial began. At the end of the first and second test blocks the word *pauze* [break] appeared on the screen. The subject could rest as long as desired and initiate the next block by a button press. In the second block, the second sentence list was tested, and in the third block the third list. The duration of the test blocks varied between 12 and 20 minutes, depending on the number of sentences tested and on the subjects' reading and response times. The subjects' speech was recorded for later analyses.

The main reason for asking the subjects to recite the sentences from memory instead of simply reading them was that this task had also been used in Ferreira's (1993) study. In addition, little is known about how speech timing is affected by the production task. When the subjects' only task is to read a set of sentences aloud, they may speak particularly carefully with the result that their speech could differ substantially from their spontaneous speech. When subjects reproduce sentences from memory, they probably focus less on their pronunciation, and the utterances may be more similar to their spontaneous speech.

Apparatus

The experiment was controlled by a Hermac 386 SX computer. The sentences were presented on a Nec MultiSync30 screen. A Sony DTC55 DAT recorder and a Senn-

heisser ME40 microphone were used to record the subjects' utterances.

Data Analyses

The speech editing system developed at the Max Planck Institute was used to digitize the experimental sentences and to perform measurements. A sampling frequency of 20 kHz was used. For each experimental sentence, the duration of the entire sentence, the noun of the first noun phrase, and the following pause were measured. A slot was defined as the time period from the beginning of the noun to the end of the following pause.

Beginnings and endings of words were determined using both acoustic and visual cues. For each measurement, a positive zero-crossing was identified in the waveform at a place that looked like a word onset or offset. It was then checked whether a word onset or offset could also be heard at that location. If not, a different positive zero-crossing was selected, and the auditory signal was checked again.

Many of the measured nouns began with voiceless stops. In these cases the energy onset could be easily determined. However, the energy onset is a dubious criterion for the word onset because the closure phase of the stop, which manifests itself as a silent interval in the speech signal, is excluded from the noun duration. This is only problematic in Experiment 5, where nouns with different word-initial consonants were compared. In all other experiments, the nouns of a sentence pair began with the same segment. Hence, the length of both nouns is likely to be underestimated by about the same time period. Nevertheless, the nouns were also measured in a different way, namely from the visible and audible offset of the preceding adjective to the noun offset. In all experiments, the same pattern of results was obtained regardless of how the nouns were measured. Therefore, for all experiments except Experiment 5, only the results for one measure of noun duration, namely the interval from the beginning

to the end of visible and audible energy, are reported.

A related problem arose in determining the duration of the pause following the noun because two thirds of the verbs in Experiments 1 through 5 began in voiceless stops. In these cases, the silent interval between noun and verb included the closure interval of the verb-initial stop. However, as the same verb appeared in both sentences of a pair, the mean duration of the "true" pauses after short and long nouns should be overestimated by about the same time interval. Each experiment included at least five sentences whose verb began with a vowel. Separate analyses of noun, pause, and slot durations yielded the same pattern of results for these as for the remaining sentences.

Sentence durations were determined by experienced research assistants. All other measurements were done by the author. While measurements for a particular sentence were performed, the results for other sentences could not be viewed. To test the reliability of the measurements, all sentence-internal measurements for one experiment were repeated by a research assistant. In 95% of the 2496 pairs of measurements, the two measurement points fell within 9 ms of each other. The experiment for which the reliability of the measurements was established is not discussed in the present paper, but will be described as part of a separate study. Its design and materials were closely related to those of Experiment 4.

Analyses of variance were performed on the durations of the nouns, pauses, slots, and sentences. Separate analyses were carried out with subjects and items as random factor. Test blocks (with three levels) and target length (long vs. short) were treated as fixed within-subjects and within-items factors.

Minor Results

Missing values. A number of utterances were excluded from the analyses because

subjects did not recite the sentences correctly, stuttered, or repaired the utterances. In addition, all utterances were discarded that included filled or unfilled pauses of 500 ms or more. Such utterances were rare; their frequency per experiment ranged between two and seven. The total number of excluded utterances per experiment varied from 27 in Experiment 1 (3% of the utterances) to 90 in Experiment 4 (10% of the utterances; mean across experiments: 6%). In each experiment, about equally many sentences with long and short targets were excluded. Across all experiments, 45% of the discarded utterances (127 utterances) had long targets, and 55% had short targets (157 utterances). In all experiments, subjects made more errors in the first than in the following test blocks; across all experiments 48% of the discarded utterances (136 utterances) stemmed from the first, 26% (75 utterances) from the second, and 26% (73 utterances) from the third block. For the analyses of variance, missing values were replaced by estimates based on subject and item means (see Winer, 1971).

Sentence durations. The durations of the experimental sentences were measured in order to determine whether differences in target or pause duration could be due to differences in speech rate. In all experiments, sentences with long targets were, on average, longer than sentences with short targets (means across experiments: 2000 vs. 1983 ms). This difference was significant by subjects, but not by items in Experiment 1 (means: 1905 vs. 1885 ms; $F(1,7) = 39.10$, $MS_e = 2037$, $p < .01$; $F(1,17) = 4.33$; $MS_e = 18373$, $p < .06$) and in Experiment 2 (means: 2088 vs. 2063 ms; $F(1,7) = 19.10$, $MS_e = 6734$, $p < .01$; $F(1,17) = 2.37$, $MS_e = 54393$). The difference approached significance in Experiment 4 (means: 2004 vs. 1974 ms; $F(1,7) = 4.62$, $MS_e = 41159$, $p < .07$; $F(1,17) = 4.29$, $MS_e = 44350$, $p < .06$) and in Experiment 5 (means: 1873 vs. 1853 ms; $F(1,8) = 5.22$, $MS_e = 183571$, $p < .06$; $F(1,17) =$

2.78, $MS_e = 34422$, $p < .12$). In all experiments, the difference in the durations of sentences with long vs. short targets was smaller than the difference in the durations of the targets themselves. The largest difference in sentence duration, obtained in Experiment 4, corresponded to a difference in speech rate of 4.48 vs. 4.35 syllables per second. Thus, there were clearly no large systematic differences in speech rate between sentences with long and short targets.

Repetition effects. As noted above, the subjects produced each sentence once in each test block. In Experiments 1 and 6, significant main effects of test block were obtained for all dependent variables. All measured durations decreased across the test blocks. Thus, the subjects apparently adopted a faster speech rate as the sentences were repeated. In Experiment 4, the main effect of test block was significant for the durations of targets and slots, which increased across the test blocks. In the remaining experiments, no significant effect of test block was obtained for any of the dependent variables. More important, the interaction of the variables test block and target length did not approach significance for any dependent variable in any of the experiments (all $p > .10$). Inspection of the data showed that in each experiment the results were highly consistent across the three blocks. Therefore, only means across blocks are reported and discussed below.

Distribution of pauses. In addition to analyzing pause durations, the distribution of pauses across the experimental condition was examined. Perhaps pauses occur more frequently in sentences with short targets than with long targets. In each of the first five experiments, pauses, defined as silent intervals of any length, were slightly more likely after short than after long targets (means across experiments: 93 vs. 92%). However, in analyses of variance of the probabilities of pauses even the largest difference, obtained in Experiment 2, did not reach significance (means: 94 vs. 85%;

$F(1,8) = 3.48$, $MS_e = 0.02$; $F(1,17) = 3.59$, $MS_e = 0.05$, $p < .10$). Thus, in Experiments 1 through 3, target length only affected the mean duration of pauses (see below); and in Experiments 4 and 5, it did not affect pauses at all. In Experiment 6, pauses were longer and significantly more frequent in sentences with short targets than in sentences with long targets (probabilities of pauses: 97 vs. 51%; $F(1,7) = 35.17$, $MS_e = 0.07$, $p < .01$; $F(1,12) = 66.14$, $MS_e = 0.06$, $p < .01$). This difference between the experiments is probably related to the fact that the difference in target durations to be compensated by pauses was much larger in Experiment 6 (117 ms) than in Experiments 1 through 3 (40 ms on average).

In Experiments 1 through 5, pauses after the target noun were very frequent. The probability of pausing varied from 91% in Experiment 1 to 96% in Experiment 3 (mean across experiments: 93%). The high probability of pauses might be due in part to the fact that the verb in about two thirds of the sentences began in a voiceless stop. Thus, sometimes the silent interval between noun and verb probably was the closure phase of the verb-initial consonant. However, even before verbs beginning with vowels, subjects paused 85% of the time. The high probability of pauses before the verb was most likely related to the fact that this location was the boundary between the main syntactic constituents of the sentence (noun phrase and verb phrase), which corresponded to separated phonological phrases. Apparently this location was consistently marked by a pause.

EXPERIMENTS 1-6

Experiment 1

Stimuli. In the first experiment, differences in target duration were introduced by varying the length of the vowel. Eighteen minimal pairs of targets such as *tak/taak* [branch/task] and *boml/boom* [bomb/tree] were tested that differed only in vowel

TABLE 1
RESULTS OF EXPERIMENT 1: MEAN DURATIONS (ms)
OF TARGETS, PAUSES, AND SLOTS AS A FUNCTION
OF VOWEL LENGTH

Measured interval	Target length		Difference (L - S)
	Long (L) (<i>taak</i>)	Short (S) (<i>tak</i>)	
Target	286	247	39**
Pause	65	76	-11*
Slot	351	321	30**

Note. When the significance levels from subject and item analyses differ, the more conservative value is indicated.

* $p < .05$.

** $p < .01$.

length. (Short vowels are indicated by single letters and long ones by double letters.)

Results. As Table 1 shows, targets with long vowels were significantly longer than targets with short vowels ($F(1,7) = 91.16$, $MS_e = 3562$, $p < .01$; $F(1,17) = 82.88$, $MS_e = 3918$, $p < .01$), and pauses were significantly shorter after long than after short targets ($F(1,7) = 8.41$, $MS_e = 2879$, $p < .05$; $F(1,17) = 12.83$, $MS_e = 1887$, $p < .01$).² The difference between the two types of targets was larger than the opposite difference between the pauses (39 vs. 11 ms). Thus, though long targets tended to be followed by shorter pauses than short targets, the differences in duration were only partially compensated for by differences in pause durations, so that the slots were still significantly longer for long than for short targets ($F(1,7) = 174.31$, $MS_e =$

² The sums of target and pause durations are not always equal to the durations of the corresponding slots. Differences are due to the way missing data were treated. Missing target and slot durations were estimated based on subject and item means across the remaining targets and slots, respectively. Pause durations were estimated in the same way, i.e., based on subject and item means across the remaining pauses. They were *not* computed as differences of estimated target and slot durations. As the estimates of pause durations were independent of the estimates of target and slot durations, the sums of targets and pauses can deviate by up to 2 ms from the corresponding slot durations.

1088, $p < .01$; $F2(1,17) = 33.22$, $MS_e = 5710$, $p < .01$). In other words, contrary to the prediction derived from Ferreira's (1993) theory, the durations of the slots were not independent of the segmental content of the syllables filling them.

Experiment 2

Stimuli. The purpose of the second experiment was to investigate whether the results of Experiment 1 could be replicated with new materials. Pairs of targets were tested that ended either in a single consonant (short targets) or in a consonant cluster (long targets). For instance, the pairs *kaas/kaars* [cheese/candle] and *pak/park* [suit/park] were used. The onset, vowel, and final consonant of the two members of a pair were identical. As in Experiment 1, 18 experimental sentence pairs were tested.

Results and discussion. The results of Experiment 2 are displayed in Table 2. Targets ending in a consonant cluster were significantly longer than targets ending in a single consonant ($F1(1,7) = 235.56$, $MS_e = 2221$, $p < .01$; $F2(1,17) = 53.59$, $MS_e = 9761$, $p < .01$). Pauses were longer after short than after long targets ($F1(1,7) = 21.75$, $MS_e = 3850$, $p < .01$; $F2(1,17) = 46.80$, $MS_e = 1789$, $p < .01$). As in Experiment 1, long and short targets differed more strongly than the following pauses so that the slots were significantly longer for long than for short targets ($F1(1,7) = 74.30$, $MS_e = 3150$, $p < .01$; $F2(1,17) = 21.05$, $MS_e = 11119$, $p < .01$).

TABLE 2
RESULTS OF EXPERIMENT 2: MEAN DURATIONS (ms)
OF TARGETS, PAUSES, AND SLOTS AS A FUNCTION
OF CODA COMPLEXITY

Measured interval	Target length		Difference (L - S)
	Long (L) (<i>kaars</i>)	Short (S) (<i>kaas</i>)	
Target	285	236	49**
Pause	92	112	-20**
Slot	379	346	33**

** $p < .01$.

A puzzling discrepancy between the present and Ferreira's findings is that in the present experiments pause durations only partially compensated for differences in target duration, whereas complete compensation was obtained in Ferreira's experiments. In Experiments 1 and 2, the targets of a pair differed in vowel length or in the composition of the coda, but shared the first and last segment. By contrast, Ferreira tested word pairs, such as *black/green*, that differed in vowel length but in most cases also in the consonants. Experiment 3 explored whether the same pattern of results as in Experiments 1 and 2 would be obtained when differences in target length were introduced by varying the final consonant of the targets. Target pairs such as *kin/kip* [chin/chicken] and *pas/pak* [step/suit] were used. Ferreira's model predicts the same result, namely complete compensation of target durations by pause durations, for this as for the preceding experiments. However, perhaps there is a gradient of compensation such that differences in the duration of the final segment of syllables are completely compensated for by pause durations, whereas differences in the duration of syllable-internal segments are only partially compensated for, depending on the segments' distance from the end of the syllable.³ If this is true, complete compensation of target and pause durations should occur in Experiment 3.

Experiment 3

Stimuli. Fourteen target pairs were used. Short targets ended in one of the stop consonants /p/, /t/, or /k/, whereas long targets ended in a liquid (/r/ or /l/), nasal (/n/ or /m/), or fricative (/f/ or /s/).

Results and discussion. As Table 3 shows, targets ending with nasals, liquid, or fricatives were significantly longer than targets ending with stop consonants ($F1(1,7) = 36.14$, $MS_e = 3859$, $p < .01$; $F2(1,13) = 44.69$, $MS_e = 3122$, $p < .01$). Pauses were

³ I am indebted to Carlos Gussenhoven for suggesting this possibility to me.

TABLE 3
RESULTS OF EXPERIMENT 3: MEANS DURATIONS
(ms) OF TARGETS, PAUSES, AND SLOTS AS A
FUNCTION OF TYPE OF CODA CONSONANT

Measured interval	Target length		Difference (L - S)
	Long (L) (<i>kin</i>)	Short (S) (<i>kip</i>)	
Target	299	270	29**
Pause	76	87	-11
Slot	376	359	17*

* $p < .05$.

** $p < .01$.

longer after short than after long targets, but this difference was only marginally significant ($F(1,7) = 4.23$, $MS_e = 5239$, $p < .10$; $F(1,13) = 3.15$, $MS_e = 7029$, $p < .10$). Slots were significantly longer for long than for short targets ($F(1,7) = 8.91$, $MS_e = 5675$, $p < .05$; $F(1,13) = 6.14$, $MS_e = 8230$, $p < .05$).

It was suggested above that differences in the length of syllable-final segments might be more likely to be fully compensated for by pause durations than differences in the length of syllable-internal segments. The results of Experiment 3 do not support this hypothesis. Although the difference in target length was smaller in this than in the preceding experiments (29 ms in Experiment 3 vs. 39 and 49 ms in Experiments 1 and 2, respectively), it was not fully compensated for by the duration of the following pause.

In the experiments reported so far, long and short targets differed systematically in their rhyme, i.e., in the vowel or coda. In the next two experiments, the target onsets were varied. Given the similarity of the results of Experiments 1 through 3, it was strongly expected that the same pattern of results would be observed again. As will be shown, however, this was not the case.

Experiment 4

Stimuli. The target pairs of Experiment 4 were similar to those of Experiment 2 in that the critical syllable constituent, which

was the onset in this experiment and had been the coda in Experiment 2, included either a single consonant (in short targets) or a consonant cluster (in long targets). The short targets began with one of the consonants /b/, /p/, /d/, /t/, or /k/. In the long targets, either /l/ or /r/ was added to form an onset cluster. For example, the target pairs *bad/blad* [bathtub/tray] and *kant/krant* [side/newspaper] were used. Eighteen sentence pairs were tested.

Results. As shown in Table 4, targets beginning with consonant clusters were longer by 45 ms than targets beginning with single consonants ($F(1,7) = 198.30$, $MS_e = 2239$, $p < .01$; $F(1,17) = 122.43$, $MS_e = 3626$, $p < .01$). The slots for long and short targets also differed by 45 ms ($F(1,7) = 100.58$, $MS_e = 4264$, $p < .01$; $F(1,17) = 35.07$, $MS_e = 12231$, $p < .01$). Finally, the durations of pauses following long and short targets were almost equal: 79 ms for short and 80 ms for long targets ($F(1,7) < 1$, $MS_e = 2682$; $F(1,17) < 1$, $MS_e = 5416$). Thus, no effect of target duration on pause duration was found.

Experiment 5

Stimuli. Experiment 5 investigated whether the results of Experiment 4 would be replicated when differences in the duration of the target onsets were created in a different way. Instead of comparing targets whose onsets included either one or two segments, targets with single-segment onsets varying in length were compared. This

TABLE 4
RESULTS OF EXPERIMENT 4: MEAN DURATIONS (ms)
OF TARGETS, PAUSES, AND SLOTS AS A FUNCTION
OF ONSET COMPLEXITY

Measured interval	Target length		Difference (L - S)
	Long (L) (<i>blad</i>)	Short (S) (<i>bad</i>)	
Target	305	260	45**
Pause	79	80	1
Slot	383	338	45**

** $p < .01$.

experiment is comparable to Experiment 3, in which targets were compared whose codas included single consonants of different length. In Experiment 5, long targets began with a nasal (/m/ or /n/) or fricative (/f/, /s/, or /z/) and short targets with a stop consonant (/b/, /d/, /p/, /t/, or /k/). For instance, the target pairs *mand/band* [basket/ribbon] and *zaad/daad* [seed/deed] were used. Eighteen experimental sentence pairs were constructed.

Results and discussion. When measured from the onset of audible and visible energy, long targets were longer by 90 ms than short ones (means: 340 vs. 250 ms; $F(1,7) = 433.41$, $MS_e = 4040$, $p < .01$; $F(1,17) = 205.21$, $MS_e = 8534$, $p < .01$). However, as the short targets began in stop consonants, a silent interval preceding the visible and audible target onset is likely to be the closure phase of the stop and should be considered part of the target. By contrast, long targets began with liquids or fricatives, and the onset of visible and audible energy can be taken to be the word onset. To obtain more comparable estimates of durations for long and short targets, the targets were also measured including any preceding silent intervals, i.e., from the offset of the preceding adjective. As there were many silent intervals before short targets and very few before long targets, this reduced the difference between long and short targets to 42 ms (see Table 5). This difference was still significant ($F(1,7) = 211.57$, $MS_e = 1752$, $p < .01$; $F(1,17) = 23.80$, $MS_e = 15571$, p

$< .01$). Slots for long and short targets (including silent intervals preceding the targets) also differed by 42 ms ($F(1,7) = 194.97$, $MS_e = 1884$, $p < .01$; $F(1,17) = 19.76$, $MS_e = 18590$, $p < .01$). Finally, the durations of pauses following long and short targets differed by only 1 ms ($F(1,7) < 1$, $MS_e = 862$; $F(1,17) < 1$, $MS_e = 3953$).

When, in the first three experiments, differences in target length were introduced by varying the vowel or coda, long targets tended to be followed by shorter pauses than short targets. By contrast, when in Experiments 4 and 5 differences in target length of approximately the same magnitude were created by varying the onset, no effect of target durations on pause durations was obtained. The experiments were carried out to test the hypothesis that differences in the durations of syllables due to the number and types of segments they include are compensated for by the duration of the following pause. The results show that there is indeed compensation, but not between syllable and pause durations. The domain of compensation cannot be the interval between syllable onsets because pause durations depended only on the length of the rhyme but not on the length of the onset of the targets. The findings are compatible with two alternative hypotheses about the domain of compensation. First, it could be the interval from the vowel of the noun to the onset of the verb. Thus, for the sentence pair *De grote boon/bon kleeft aan het bord* [The big bean/ticket sticks to the plate], the domain of compensation could extend from the vowel of the noun *boon* or *bon* to the onset consonant of the verb *kleeft*. This would imply that pause durations depend on the durations of syllable rhymes but not onsets. Second, the domain of compensation could be the interval between successive vowels. In the above sentence pair the domain of compensation would then extend from the vowel of the noun to the vowel of the verb. On this hypothesis, the duration of a pause would de-

TABLE 5
RESULTS OF EXPERIMENT 5: MEAN DURATIONS (ms)
OF TARGETS, PAUSES, AND SLOTS AS A FUNCTION
OF TYPE OF ONSET CONSONANT

Measured interval	Target length		Difference (L - S)
	Long (L) (<i>zaad</i>)	Short (S) (<i>daad</i>)	
Target	342	300	42**
Pause	78	79	-1
Slot	421	379	42**

** $p < .01$.

pend on its left and right context, i.e., on the duration of the preceding syllable rhyme and the following syllable onset.

To decide between these hypotheses, an experiment was carried out in which the context to the right of the measured pauses was varied. Subjects produced pairs of sentences differing in their verbs, such as *Het hele dorp vindt/acht onderzoek noodzakelijk* [The whole village finds/considers an investigation necessary]. One of the verbs, called consonant-verb hereafter, began with a consonant or consonant cluster, whereas the other, called vowel-verb, began with a vowel. In this experiment, the noun of the first nominal phrase, which was varied in Experiments 1 through 5, was the same for both members of a sentence pair. If the domain of compensation only includes the rhyme of the noun and the following pause and ends at the beginning of the verb, the duration of the pause should be independent of how the verb begins. Thus, in the above sentence pair, the mean durations of the pauses preceding *vindt* and *acht* should be identical. By contrast, if the domain of compensation is the vowel-to-vowel interval, the duration of the consonantal onset in consonant-verbs should be compensated for by the duration of the preceding pause, resulting in shorter pauses before consonant-verbs than before vowel-verbs. Thus, in the above sentence pair the pause should, on average, be longer before *acht* than before *vindt*.

Experiment 6

Stimuli. Thirteen pairs of experimental sentences differing in their verbs were tested. One of the verbs of a pair began with a vowel, the other with a fricative, nasal, liquid, or fricative-nasal cluster. All verbs were monosyllabic. The verbs of a pair were matched in vowel length. It was not possible to find minimal pairs of verbs differing only in whether or not they included a consonantal onset.

Results and discussion. The results of Experiment 6 are summarized in Table 6.

The mean durations of the first noun of the sentences, corresponding to the target in the earlier experiments, did not differ significantly in the two experimental conditions ($F(1,7) = 3.86$, $MS_e = 825$, $p < .10$; $F(1,12) = 1.01$, $MS_e = 3152$). This was expected, as the same noun appeared in both members of a sentence pair. The slots, measured as in the preceding experiments from noun onset to verb onset, were longer by 63 ms before vowel-verbs than before consonant-verbs ($F(1,7) = 41.11$, $MS_e = 14826$, $p < .01$; $F(1,12) = 42.91$, $MS_e = 14204$, $p < .01$). Thus, vowel-verbs were preceded by longer pauses than were consonant-verbs ($F(1,7) = 41.45$, $MS_e = 11970$, $p < .01$; $F(1,12) = 66.13$, $MS_e = 7504$, $p < .01$).

As in the preceding experiments, partial compensation was observed: The mean duration of the consonantal onset of consonant-verbs, defined as the interval from the beginning of the verb to the beginning of the vowel, was 117 ms, whereas the difference in the durations of the pauses preceding vowel-verbs and consonant-verbs was only 57 ms. The slots preceding vowel-verbs were compared to the intervals including the slot and the onset consonant of consonant-verbs. Thus, the left margin of the measured interval was the beginning of the noun, and the right margin was the beginning of the vowel of the verb. These intervals were significantly longer for consonant-verbs than for vowel-verbs (means: 387 vs. 441 ms; $F(1,7) = 41.80$, $MS_e =$

TABLE 6
RESULTS OF EXPERIMENT 6: MEAN DURATIONS (ms)
OF NOUNS, PAUSES, AND SLOTS AS A FUNCTION OF
VERB TYPE

Measured interval	Verb type		Difference (V - C)
	Vowel (V) (<i>acht</i>)	Consonant (C) (<i>vindt</i>)	
Noun	286	282	4
Pause	101	44	57**
Slot	387	324	63**

** $p < .01$.

10692, $p < .01$; $F2(1,12) = 9.46$, $MS_e = 47265$, $p < .01$). If the compensation for the duration of the consonantal onset by the preceding pause were complete, these intervals would be the same.

The results of Experiment 6 prompted an additional analysis of Experiment 4. Given that in Experiment 6 pause durations depended on whether or not the following word included a consonantal onset, one might expect that the duration of the consonantal onset should also affect the duration of the preceding pause. In Experiment 4, targets began either with a single consonant or a cluster (as in the pair *bad/blad* [bathtub/tray]). No effect of this difference on the durations of the pauses *following* the targets was obtained. However, the results of Experiment 6 suggest that there might be an effect on the pauses *preceding* the targets. Indeed, the interval between the end of the adjective and the onset of the target noun was significantly shorter when the target began in a cluster than when it began in a single consonant (means: 39 vs. 49 ms; $F1(1,7) = 13.19$, $MS_e = 1769$, $p < .01$; $F2(1,17) = 10.16$, $MS_e = 2298$, $p < .01$). As the targets began in stop consonants, the preceding silent interval included the closure phase of the stop, and the presence or absence of a second onset consonant may have affected its duration. At any rate, it appears that variations in onset durations are partially compensated for by initiating the auditory syllable onset at slightly different moments relative to the preceding syllable offset.

To summarize, Experiments 1 through 5 showed that pause durations were affected by the duration of the rhyme, but not by the duration of the onset of the preceding syllable. Experiment 6 showed that pause durations depended on whether or not the following syllable included a consonantal onset, and the reanalysis of Experiment 4 revealed that they were affected by the length of the following syllable onset. Thus, pause durations depended on the durations of the preceding syllable rhyme and the fol-

lowing syllable onset. The implications of these results will be considered in the next section.

GENERAL DISCUSSION

Phoneticians have provided us with detailed knowledge of various temporal properties of speech. We know, for instance, how long different segments in a given language typically are, and how their durations are affected by contextual influences, such as their syllable, word, and sentence position (see Introduction for details and references). Yet, very little is known about how these temporal regularities arise. An interesting proposal concerning this question was made by Ferreira (1993). Ferreira's model has two parts. The first part describes how the intervals between successive syllable onsets, called slots here, are determined. The second part is a quantitative model specifying how these slots are divided into syllable and pause durations. An interesting prediction following from the first part of the model is that the slot for a particular syllable should depend only on its position in the prosodic structure, and not on its segmental content. Ferreira reports two experiments in which this prediction is borne out. In these experiments, she found that in sentences such as *The black/green table tempted me*, targets of different length (*black/green* in the example) appeared in slots of equal duration.

The results of the present experiments, however, are only partly consistent with Ferreira's model. When the length of the targets was varied by changing their rhyme, an inverse relationship of target and pause durations was found, as predicted by the model. However, three unexpected findings were obtained. First, according to the model, slots are created first and then partitioned into syllable and pause durations. Therefore, *complete* compensation of target and pause durations was predicted. Yet, only partial compensation was obtained. Second, as the slots are independent of the segmental content of the syllables filling

them, compensation of differences in syllable duration by the duration of the following pause should occur no matter how these differences are introduced. Yet, compensation was obtained only when long and short targets differed in their rhymes, not when they differed in their onsets. Finally, the duration of a pause should depend only on the segmental content of the preceding syllable, which belongs to the same slot, and not on the segmental content of the following syllable, which belongs to a different slot. Yet, in Experiments 4 and 6, right-context effects on pause durations were obtained.

Ferreira's model was developed for American English, not for Dutch. One interpretation of the current findings is that the two languages, unexpectedly, differ in their timing principles.⁴ Whether this is true is currently being investigated in a cross-linguistic study, in which speakers of the two languages produce structurally similar sentences in the same experimental environment. Until further evidence is available, it seems most appropriate to assume that Ferreira's model is a good account of timing in American English, but that certain modifications of the model are necessary to account for the Dutch data. The following discussion focuses on the question of what these modifications might be.

An important result of the present experiments is that in Dutch, slots are not independent of the segmental content of the syllables that fill them. The data do not reveal which segmental properties influence slot durations. Clearly, more information is relevant than the number of segments alone

because slots were found to depend not only on the number but also on the types of target segments. However, it cannot be inferred from the available data which distinctions between segments are relevant; whether, for instance, slots only depend on which broadly defined classes (such as plosives or nasals) the segments belong to, or whether differences between segments within such classes also affect slot durations.

Recall that in Ferreira's model slots are built in two steps: First, on the phonological level, a metrical grid is constructed, in which one beat is automatically associated with each syllable and extra beats are inserted to mark the boundaries of prosodic constituents. Then, on the phonetic level, the time intervals between syllable onsets are computed depending on the number of beats assigned to each syllable. Both of these steps are independent of segmental information. Thus, the model assumes that at the phonological level, segmental and metrical information is represented independently of each other, and it ascribes a specific phonetic effect to metrical information, namely that the number of beats associated with each syllable is represented in the speech signal in the intervals between syllable onsets. The present findings suggest that for Dutch this view cannot be entirely correct. One way to account for the results is to modify the model such that the association of beats to syllables at the phonological level, or the translation of the distribution of beats into slots at the phonetic level, or both, becomes sensitive to segmental information. Note that this proposal only concerns the first part of Ferreira's model, which describes how slots are generated, and not the second part, which describes the partitioning of slots into syllable and pause durations. Regardless of how slots are created, syllable and pause durations within slots could still be derived as stated in that part of the model.

Alternatively, one could attempt to account for the present data within a model that does not include the concept of slots.

⁴ The durational differences between long and short targets were comparable in the two studies. In Ferreira's two experiments, long and short targets differed by 39 and 32 ms, respectively (corresponding to 13% of the short target duration in both cases). In Experiments 1 through 3 above, the two types of targets differed by 39, 49, and 29 ms, respectively (corresponding to 16, 21, and 11% of the short target durations, respectively). Thus, it was not the case that the target differences in the present study were simply too large to be fully compensated for.

In Ferreira's model, slots are the output of a set of processes that rely only on prosodic, not on segmental, information. However, in all of the above experiments slots depended on segmental information. (Most likely they also depended on prosodic information, but this was not tested.) Hence, it could be argued that there is no set of processes that derives slots based solely on prosodic information and that, therefore, a theory of timing should not refer to the notion of slots defined as the output of such processes. Instead of postulating one set of processes that creates slots and another set that divides them into syllable and pause durations, one could postulate just one set of processes that derives syllable and pause durations directly.

In Ferreira's quantitative model, slots play a crucial role: The duration of a syllable is computed as its minimal duration plus a certain amount of lengthening, which is a proportion of the slot in which the syllable appears; and the duration of the pause following the syllable is the difference of the slot and syllable durations. In a model that does not include the concept of slots, syllable and pause durations must obviously be derived in a different way. Conceivably, the duration of a syllable could still be derived as the sum of its minimum duration and some amount of lengthening, but the degree of lengthening could depend on the number of beats associated with the syllable rather than on the slot duration. This would imply that all syllables appearing in the same position in the prosodic structure would be lengthened by the same amount. Alternatively, the amount of lengthening of a syllable could depend both on the number of associated beats and on its segmental content so that different syllables could be lengthened by differing amounts. Pause durations could be based on the number of associated beats and on segmental properties of the surrounding syllables.

Thus, there are at least two ways to account for the Dutch data. One way is to assume two processing components, one

that computes slots and one that divides them into syllable and pause durations. The crucial difference from Ferreira's model is that the component generating slots must have access to segmental information. A second way to account for the results is to give up the idea of two separate processing components and to postulate just one component that derives syllable and pause durations directly from metrical and segmental information without computing slots first. The present data do not suffice to specify a quantitative model of Dutch syllable and pause durations because they do not reveal how much different types of syllables are lengthened and how long pauses occurring in different contexts are. Hence, it cannot be determined which type of model predicts Dutch syllable and pause durations most accurately.

In Ferreira's theory, compensation of syllable by pause durations is a necessary consequence of the "blindness" of the slot-generating processes to the segmental content of the utterance. Compensation arises at the phonetic level when the slots, whose durations have been specified without access to segmental information, are divided into syllable and pause durations. The present data suggest, however, that either the processes generating slots are not blind to segmental information, or else that slots are not generated at all. Neither of these possibilities implies an account of the compensatory tendency. Moreover, the domain of compensation is the vowel-to-vowel interval, which does not correspond to any independently motivated phonological or phonetic unit. This interval always spans a syllable boundary and often a word and phrase boundary as well. Vowel-to-vowel intervals do, however, play an important role at the articulatory level, as will be shown below. This suggests that the compensatory effect might not arise during phonological or phonetic encoding at all, but might be due to certain articulatory tendencies. This does not imply that at the phonetic level, the timing of utterances is not

captured at all, or that it is independent of segmental information. It only implies that one particular type of segmental information, namely the intervals between successive vowels, is not relevant for the determination of utterance timing at that level.

The proposal that the compensatory effect might arise at the articulatory level is based on a hypothesis suggested by Fowler (1979, 1983) to explain the results of so-called perceptual center (P-center) experiments. In these experiments, subjects are asked to produce sequences of syllables (such as *ba-ma-ba-ma*) at regular intervals or to adjust the intervals between auditorily presented syllables until they appear evenly timed (e.g., Fowler, 1979; Marcus, 1981; Morton, Marcus, & Frankish, 1976). In both cases, subjects do not create sequences with evenly timed syllable onsets, but produce systematic deviations from onset isochrony. Hence, the syllables' P-centers, i.e., the events that occur regularly in perceptually regular sequences, are not syllable onsets. The location of P-centers tends to correlate with certain parts of the speech signal, in particular with the durations of the syllable onset and rhyme, but it does not correspond to any particular acoustic landmark, such as the onset of the vowel or its peak (e.g., Cooper, Whalen, & Fowler, 1988; Fowler, 1979; Fox & Lehiste, 1987; Marcus, 1981; Pompino-Marschall, 1989, 1990).

Fowler and co-workers (Fowler 1979, 1983; Fowler & Tassinari, 1981; Tuller & Fowler, 1980) have proposed that the localization of P-centers can best be understood by considering the articulatory movements underlying the production of syllables. When asked to produce an evenly timed sequence of syllables, speakers probably initiate vocalic gestures at regular intervals. This does not necessarily lead to isochrony of the acoustic onsets of syllables or vowels because the articulation of different consonants begins at different moments before the articulation of the vowel and overlaps with it to varying degrees (e.g., Butcher &

Weiher, 1976; Carney & Moll, 1971; Kent & Moll, 1972; Öhmann, 1966; Perkell, 1969).

Thus, subjects in P-center experiments probably produce vocalic gestures at regular intervals. Fowler (1983) speculates that a tendency toward regular vowel production might also exist in spontaneous speech. As has often been noted, languages sound rhythmical, not only in the sense that strong and weak units alternate, but also in the sense that certain events seem to recur at regular intervals. In syllable-timed languages, such as Spanish and Italian, the subjectively evenly timed units are syllables, and in stress-timed languages, such as English and Dutch, they are the intervals between stressed syllables (e.g., Abercrombie, 1964; Catford, 1977; Pike, 1945). Though the impression of isochrony is strong, its acoustic correlate has not been identified (e.g., Dauer, 1983; Lehiste, 1973, 1977). Fowler's suggestion is that the impression of isochrony in stress-timed languages might, at least in part, be based on the regular initiation of the gestures for stressed vowels.

As Fowler (1977, 1983) argues, regularity of vowel production could arise without explicit coding of intervocalic time intervals in the speech plan, but could be a consequence of the organization of the speech motor system. All vowels are produced as relatively slow changes in the global shape of the vocal tract (e.g., Perkell, 1969). Presumably, the invariances across vocalic gestures are captured in a dedicated muscle system, a so-called coordinative structure (e.g., Fowler, Rubin, Remez, & Turvey, 1980; Kelso, Tuller, & Harris, 1983). In fluent speech, this coordinative structure is cyclically activated, once for each stressed vowel, so that one stressed vowel is produced immediately following the other. For each stressed vowel, the coordinative structure is specified somewhat differently. The gestures for unstressed vowels and consonants are superimposed onto those for stressed vowels.

Thus, both the results of P-center experiments and the impression of isochrony in stress-timed languages might be due to the cyclic operation of the coordinative structure for stressed vowels. The compensatory effect observed in the present experiments might have the same basis, i.e., it might be an instance of the general tendency toward regular production of stressed vowels.

To summarize, syllable and pause durations in spoken utterances are determined by a number of factors. As described in the Introduction, there are segmental effects on syllable durations and effects of prosodic structure, such as final lengthening and the insertion of pauses at phrase boundaries. These phonological effects can be captured in a quantitative model like the one proposed by Ferreira (1993), which predicts syllable and pause durations based on segmental and prosodic information. As pointed out in the Introduction, the fact that such a model accurately predicts syllable and pause durations does not mean that speakers necessarily carry out the same types of computations. Instead of determining time intervals, prosodic and segmental information might control certain articulatory parameters. Thus, articulatory gestures are the *target* of control. In addition, properties of the articulatory system, such as the cyclicity of vocalic gestures, modify the phonologically specified timing of utterances. Thus, the temporal characteristics of speech are the joint product of a number of influences arising at different levels of processing.

APPENDIX

Experimental Sentences of Experiments 1–6

Experiment 1. De nieuwe *baan/ban* kweekt veel onrust. De brede *beek/bek* pronkt op de foto. De grote *boom/bom* treft hun nieuwe huis. De groene *boon/bon* kleeft aan het boord. De arme *Deen/den* knapt onder de last. De laatste *doop/dop* trekt veel aandacht. De bruine *kaap/kap* oogt nogal vreemd. De luide *kliek/klik* teistert de zenuwen. De laatste *knaak/knak* eindigt het spel. De gouden *knoop/knop* oogst veel bewondering.

De slimme *koop/kop* komt goed van pas. De oude *kraam/kram* tergt de bureu. De lange *peen/pen* perst tegen het deksel. De dikke *peet/pet* eist veel aandacht. De zwarte *pook/pok* ergert de vrouw. De houten *poot/pot* plonst in de vijver. De zware *taak/tak* prikkelt hun fantasie. De derde *toon/ton* klingt nogal hol.

Experiment 2. De houten *balk/bak* plonst in de vijver. De roze *band/Het roze bad* past bij de tegels. De nieuwe *bond/Het nieuwe bod* ergert de burgemeester. Het witte *bont/bot* komt uit Italië. De Engelse *dans/das* oogst veel bewondering. De lichte *dolk/Het lichte dok* drijft in het vieze water. De gele *kaars/kaas* kleurt goed bij het tafelkleed. De grijze *kaft/kat* oogt zeer geheimzinnig. Het zware *kamp/De zware kap* eist veel kracht. De grote *krans/kras* trekt zijn aandacht. De oude *krant/Het oude krat* komt in de kelder. Het verwaarloosde *pand/pad* eist veel onderhoud. Het Franse *park/pak* oogt zeer aantrekkelijk. Het verse *perk/De verse pek* trekt de kleuters aan. De oude *port/pot* kost veel geld. De grote *prent/pret* komt op het goede moment. Het laatste *punt/De laatste put* krijgt veel kritiek. De witte *talk/tak* plakt aan zijn handen.

Experiment 3. De rode *ball/bak* plonst in de rivier. De donkere *bar/Het donkere bad* ergert de diplomaat. De zware *bom/Het zware bot* komt snel naar beneden. De witte *bon/bok* oogt veel te groot. De fraaie *duif/duik* oogst veel bewondering. De glazen *kas/kat* breekt veel te makkelijk. De ronde *kin/kip* komt op de foto. De ijzeren *klem/klep* kost veel te veel. De oude *knoll/knop* opent het hok. De Griekse *kom/kok* trekt veel toeristen aan. De vieze *kuif/kuip* ergert de werkster. De vette *kluif/kluit* past niet in het vat. De nieuwe *pas/Het nieuwe pak* breekt met de traditie. De nieuwe *tas/tap* komt net op tijd.

Experiment 4. De eerste *blaar/baar* oogt veel te groot. Het rare *blad/bad* krijgt veel kritiek. De vreemde *bles/bes* komt steeds vaker voor. Het witte *blok/De witte bok* past net in de schuur. De leuke *broek/Het leuke boek* past goed bij de collectie. De oude *bron/bon* krijgt een vervanger. De rijke *boer/broer* koopt de gele bus. De slechte *draad/daad* kost enkele doden. De harde *drop/dop* kost bijna niets. De grote *klas/kas* eist veel onderhoud. De tweede *klap/kap* komt erg hard aan. De arme *klerk/kerk* erft de schat. De zachte *klik/kik* ergert de luisteraar. De scherpe *kram/kam* prikt het kind. De andere *krant/kant* opent het debat. Het rode *krat/De rode kat* ploft op straat. De zwarte *plek/pek* trekt de kleuters aan. De hoge *trap/tap* ergert de kelner.

Experiment 5. De felle *fikt/tik* eechoot nog lang na. Het oude *fort/De oude port* ademt een voorname sfeer. De kleine *fuif/duif* kost veel te veel. De ronde *fuik/buik* pronkt of de foto. De hoge *fust/kust* prikkelt de verbeelding. De vuile *mand/band* krijgt een nieuw verfje. De oude *melk/kelk* plakt aan de tafel. De grote *mok/Het grote dok* past niet bij de rest. De snelle *nar/dar* komt bij de koningin. De lange *nerf/kerf* eist veel geduld. De witte *non/bon* trekt veel aandacht. De lauwe *sap/tap* koelt snel af. De laatste *som/kom* telt

niet meer mee. De hoge *soort/foort* eist veel onderhoud. De vieze *sop/dop* ergert de werkster. Het goede *zaad/De goede daad* komt net te laat. De grote *zak/bak* ploft op straat. Het nieuwe *zerk/perk* trekt veel bezoekers aan.

Experiment 6. De jonge smid *leert/laardt* in het nieuwe bedrijf. Het grijze bad *lijkt/loogt* nog steeds heel vies. De andere groep *maakt/uit* bezwaren tegen het plan. De slimme klant *sloopt/lijkt* de weegschaal. De kwade Griek *splijt/leert* het mariabeeld. De oude vriend *steekt/ent* een mooie appelboom. De onbeschaafde vent *stort/int* zijn geld. De leuke bruid *streekt/laait* de cavia. De vrolijke Turk *verft/lerft* de antieke tafel. Het hele dorp *vindt/acht* onderzoek noodzakelijk. Het witte pak *vraagt/leest* veel aandacht. De grijzende vorst *wenst/leest* een stilleven. De hevige vloed *zakt/leht* langzaam weg.

Note. Targets are italic. In each pair, the long target is listed first.

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