8-1-2005

Perceptual Effects of Preceding Non-Speech Rate on Temporal Properties of Speech Categories

Travis Wade
Carnegie Mellon University

Lori L. Holt
Carnegie Mellon University, lholt@andrew.cmu.edu

Perceptual effects of preceding non-speech rate on temporal properties of speech categories

Travis Wade and Lori L. Holt

Department of Psychology and Center for the Neural Basis of Cognition

Carnegie Mellon University

Correspondence:

Travis Wade

Department of Psychology

Carnegie Mellon University

5000 Forbes Avenue

Pittsburgh, PA 15213

Phone: (412) 268-8393

Email: twade@andrew.cmu.edu

Running head: Perceptual effects of preceding non-speech rate

Abstract

The rate of context speech can influence phonetic perception. This study investigated the bounds of rate-dependence by observing the influence of non-speech precursor rate on speech categorization. Three experiments tested effects of pure-tone precursor presentation rate on perception of a [ba]-[wa] series defined by duration-varying formant transitions that shared critical temporal and spectral characteristics with the tones. Results showed small but consistent shifts in the stop-continuant boundary distinguishing [ba] and [wa] syllables as a function of the rate of precursor tones, across various manipulations in the amplitude of the tones. The effect of the tone precursors extended to the entire graded structure of the [w] category as estimated by category goodness judgments. These results suggest a role for durational contrast in rate-dependent speech categorization.

Perceptual effects of preceding non-speech rate on

temporal properties of speech categories

Since speech unfolds over time, rate is a potential source of variability in the realization of phonological contrasts whose primary cues are temporal. Indeed, it is readily observable that time cues to contrasts involving vowel identity (e.g., Gay, 1978; Port, 1981), gemination (e.g., Pickett & Decker, 1960), consonant voicing (e.g., Miller, Green, & Reeves, 1986; Summerfield, 1975), and manner of articulation (Mack & Blumstein, 1983; for review, see Miller, 1981; 1987; Miller & Baer, 1983) vary substantially in their realization across speaking rates. The result is often overlapping classes of sounds not readily separable by time-invariant criteria. However, human perceivers appear to overcome this variability by interpreting the relevant acoustic cues in what may be described as a rate-dependent manner. For example, listeners' perceptual categorization boundaries for a series of stimuli varying acoustically in the duration of an initial formant transition and perceptually from [ba] to [wa] steadily increase along the formant-transition duration dimension (such that there are more [ba] responses) when rate, as conveyed by overall syllable duration, decreases (Miller & Liberman, 1979). This shift parallels the shift observed in speech production; formant transition durations are typically longer in slower speech. Thus, rate-dependent perception appears to compensate for patterns in the natural language environment.

There is some indication that this rate-dependence is diminished, and perhaps is less necessary, when targeted contrasts possess more complex, natural sets of cues. For example, Shinn and colleagues (1984; 1985) observe that the effect of syllable length on perception of the [b] versus [w] distinction gradually disappears as [b] and [w] tokens are

synthesized in a less stylized manner and are differentiated by additional, non-temporal cues such as formant onset frequencies and formant-frequency trajectories. However, Miller and Wayland (1993) show that in the presence of multi-talker babble noise, rate-dependent category boundary shifts hold up even without these additional cues, suggesting that rate-dependent categorization is useful in natural speaking situations.

Parallel findings of rate dependence in perception of other temporal contrasts are abundant (e.g., Ainsworth, 1974; Fujisaki, Nakamura, & Imoto, 1975; Summerfield, 1981). Furthermore, it has been demonstrated that speaking rate affects not only the locations of perceptual category boundaries, but also the internal structure of the categories. When trained participants rate consonants as voiceless stops based on voice onset time (VOT, Miller & Volaitis, 1989b) or glides based on formant transition durations (Miller, O'Rourke, & Volaitis, 1997), entire category goodness rating curves, including both ends of best-exemplar ranges, shift with changes in speaking rate. As speaking rate decreases, stimuli with increasingly longer formant transition durations are judged to be the best-sounding [w] category members. This is in marked contrast to patterns observed for other, higher-level factors affecting phonetic categorization; the effects of lexical status, for example, seem to be limited to ambiguous boundary regions and do not affect overall category structure (Allen & Miller, 2001).

The standard interpretation of the pervasive perceptual effects of rate is that they serve to accommodate recovery of intended phonetic units; that is, perception is mediated by knowledge of the rate-dependent nature of temporal contrasts, or recovery of their articulatory sources (e.g., Fowler, 1980; Fowler, 1990; Miller & Baer, 1983; Summerfield, 1981). One observation that might give pause to such a causal view of the

link between production and perception is that listeners generally fail to compensate optimally for the rate-dependent patterns that actually occur in speech. For example, continuous increases in formant transition lengths of English onset [w] glides (Miller & Baer, 1983) and in VOT duration of syllable-initial [p] consonants (Miller et al., 1986) have been observed for speech produced across very fast to very slow speaking rates. Pairing these speech production measurements with similar observations of rate-dependent [b] productions, it is possible to calculate optimal rate-dependent shifts in perceptual boundaries for consonant voicing and manner of articulation. However, listener categorization reflects these patterns of speech production only qualitatively and, particularly for the [b]-[p] boundary, perceptual shifts are more limited and negatively accelerated at longer VOT values (Miller et al., 1986) than is predicted from production measurements. Pind (1995) has observed a similar pattern for VOT in Icelandic consonants.

Miller and colleagues offer two possible explanations for such inconsistencies: 1) limits on the flexibility of perceptual boundaries and 2) limits on the effect of later-occurring information (syllable duration) on categorization (Miller et al., 1986). An alternative explanation is that rate-dependent categorization patterns do not actually reflect detection of, and compensation for, the rate of articulation at all, but rather stem fortuitously from perceivers' sensitivity to the rate of auditory events more generally. It is well known that sensorineural systems are more sensitive to change than to absolute levels in perceived signals, enabling them to process stimuli over wider physical ranges than would otherwise be possible (e.g., Purves & Lotto, 2002). Such contrastive perceptual patterns are in line with the directionality of rate-dependent speech

categorization. Faster speech contexts result in perception of subsequent temporal information as relatively slower than the same information preceded by slower context stimuli. Contrast may have additional benefits in speech perception, since due to vocal tract mechanics and coarticulation the absolute physical properties of speech events are highly influenced by adjacent events. It has been suggested, in fact, that much of the observed context dependence in speech perception results from a tendency to perceive acoustic events in a relative manner (Holt, in press; Holt & Kluender, 2000; Kluender, Coady, & Kiefte, 2003; Lotto & Kluender, 1998; Lotto, Kluender, & Holt, 1997). Along these lines, Diehl and Walsh (1989) assert that apparent speaking rate effects may result from durational contrast, whereby temporal cues such as the length of an acoustic segment are perceived relative to nearby segments rather than absolutely. Thus, for example, listeners may accept longer formant transitions for [b] at slower speaking rates not because they reveal something about typical articulation, but simply because they appear shorter by contrast to longer surrounding segments, a pattern previously documented for non-speech tone durations (Goldstone, Boardman, & Lhamon, 1959; Goldstone, Lhamon, & Boardman, 1957; Walker & Irion, 1979; Walker, Irion, & Gordon, 1981). Oller and colleagues (1991) speculate further on the precise workings of a durational contrast effect. To account for the nonlinear relation of boundary shifts and apparent rate, they introduce a “comparable range model” whereby contrast effects only occur between two sounds (e.g., a transition and following steady state) with absolute durations falling within a similar range, perhaps within a 1:1 to 1:2 ratio. Oller et al. also introduce a possible mechanism (“pivot point error”) to account for the effect, postulating

that a sluggishness in perceptual recognition of a change in formant trajectory results in perceptual overestimation of the duration of transitions preceding short vowels.

Some evidence that “speaking rate” effects are not unique to speech was offered by Pisoni, Carrell and Gans (1983), who observed boundary shifts analogous to those found for speech (Miller & Liberman, 1979) when listeners characterized non-speech sine wave approximations of [ba]-[wa] formant transitions with different durations as either ‘abrupt’ or ‘gradual’. Addressing concern that these sounds may have been too speech-like, Diehl and Walsh (1989) achieved the same effect with single frequency-modulated sine wave stimuli. Whether stimuli tracked a normal bilabial F1 frequency trajectory or a reverse pattern that is impossible in normal speech, participant classification of transition abruptness was robustly dependent on overall stimulus length.

The significance of these and similar findings has been challenged, perhaps most notably by Fowler (1990; see also Fowler, 1992), on the grounds that perception of non-speech analogs cannot be directly compared to speech perception, since speech has a clear, identifiable environmental source whereas non-speech analogs to speech (pure tones, for example) do not. Fowler bolsters this argument with comparison of perception of a set of natural recordings of sounds produced by real mechanical events and sine-wave analogs of these sounds. Listeners showed contrastive perceptual patterns in the classification of the sine-wave analogs, but perception of the natural events the sine-waves modeled was contrastive in some cases, but not in others. Thus, contrary to the expectations of a durational contrast account, in some cases, perception of the event and its sine-wave analog diverged despite the fact that their acoustics shared common temporal characteristics. Fowler argues that this is because whereas the events possessed

a real acoustic source that could be apprehended from the waveform, the sine-wave analogs did not. By analogy, Fowler suggested that studies investigating perception of non-speech stimuli are uninformative in understanding speech perception because speech, like the mechanical events, originates from an environmental source whereas the simple non-speech analogs do not. Perception of the two classes of stimuli, by this view, arises from different origins.

Perhaps informative to these theoretical positions are additional data from studies with infant and non-human participants. Infants demonstrate rate-dependent perception of the [b]-[w] contrast, responding to more sounds as [w] before shorter vowels in a sucking-habituation study (Eimas & Miller, 1980). So do budgerigars, which have the ability to mimic human sounds using a suprasyringeal cavity (Dent, Brittan-Powell, Dooling, & Pierce, 1997) and Japanese macaques, which do not (Sinnott, Brown, & Borneman, 1998). These studies indicate that significant knowledge of rate-dependent speech patterns may not be necessary for rate-dependent speech categorization. Nevertheless, these results do not do much to differentiate whether rate-dependent speech perception arises from general perceptual mechanisms like durational contrast or from recovery of the environmental source (i.e., the articulatory gestures), as suggested by Fowler (1990). Either a sufficiently developed auditory system, or alternatively, a sufficiently general ability to directly recover the natural (articulatory) sound source could potentially account for infant and non-human patterns of behavior.

Thus, despite differing theoretical accounts, the present data by and large leave open the question how rate-dependent speech categorization arises. Nevertheless, Fowler's (1990) criticism does reveal theoretical limitations of experimental designs in

which the nature of stimuli (speech vs. non-speech) is manipulated and compared across experiments or conditions. In determining the nature of rate-dependent speech perception, it is informative to test not only whether context rate affects speech and non-speech perception in the same way (Pisoni et al., 1983; Diehl & Walsh, 1989), but also whether rate effects observed for *speech* may be elicited by manipulation of the rate of non-speech contexts that are not readily attributable to an articulatory source. The present study was designed to test this possibility.

The studies of rate-dependence in speech perception discussed so far have concentrated primarily on a single source of rate-relaying context, namely the length of the vowel immediately following a target segment. Indeed, the vast majority of studies to date have manipulated duration of target-adjacent segments, since nearby sounds appear to play a critical role in determining a context rate. Newman and Sawusch (1996), for example, observed that rate of non-adjacent speech following a target segment affected its perception only if they fell within a short (around 300 ms) window after the target. This apparent primacy of local segments in driving rate effects is consistent with intrinsic models of timing (e.g., Fowler, 1980; Summerfield, 1981) that assume perception mainly considers a target segment's immediate articulatory context when accounting for rate.

For the aims of the present study, this stimulus paradigm is unsuitable. Substitution of target-adjacent segments with non-speech acoustic events is problematic, since these segments often overlap acoustically with the target, carrying critical information as to its identity. However, it is also known that rate information further removed from a given sound can affect its phonetic categorization (e.g., Kidd, 1989; Summerfield, 1981) and internal category structure (Wayland, Miller, & Volaitis, 1994).

The present study, therefore, adopts methods from these latter studies, using sentence-length non-speech sequences as precursors to target speech segments. A series of experiments was designed to measure the perception of formant transition durations as cues to the [b]-[w] distinction and [w] category goodness in the presence of these precursors, to determine whether non-speech as well as speech contexts can affect speech categorization of stimuli defined by a temporal acoustic cue.

Gordon (1988) takes an important step in showing that the rate information cued by more temporally-distant events may not be entirely speech-specific in nature, observing that the rate of a preceding carrier sentence can influence a consonant voice distinction even when the sentence is severely degraded (by low-pass filtering at 375 Hz or imposing its amplitude envelop on a sine wave, but not on white noise). Gordon stops short of suggesting that the effects are contrastive or general in nature, however, addressing only which aspects of the speech signal might be responsible for syllable-extrinsic rate detection.

Of studies that have tested directly for non-speech effects on temporal speech contrasts, a notable failure of non-speech rate to influence speech categorization is reported by Summerfield (1981). In this study, listeners heard a portion of a familiar tune followed by a syllable. Listeners' judgment of the syllable's initial consonant ([b] vs. [p]) was not affected by the rate of the melody, although the length of the following vowel did have an effect. Within a durational contrast account of rate effects, there is at least one major reason to predict this null result [see also Gordon (1988) for more general reasons]. Whereas the precise workings of durational contrast are as yet unclear, it seems that some degree of spectral continuity (Walker & Irion, 1979) and temporal similarity (Oller et al.,

1991) are necessary between contrast-providing context and target stimuli. In the case of phonetic contrasts such as stop-continuant ([b]-[w]) and voiced-voiceless ([b]-[p]), temporal cues for which rate-dependent perception have been investigated include voicing offset and formant transitions. Both of these acoustic events involve temporal durations in the range of tens of milliseconds, and both (particularly the stop-continuant distinction) involve critical spectral movement in the F1-F2 range. Summerfield's melodic precursors, on the other hand, were composed of tones with durations of hundreds of milliseconds, on the order of the syllable duration rather than the duration of the syllable-initial VOT that distinguished stimuli. These tones, described as "machine-like buzzes," did contain spectral energy in speech formant ranges, with two resonances held constant at 1.0 and 3.0 kHz and a third oscillating at 100 Hz between 1.5 and 2.5 kHz. However, the melodic line, for which rate was varied, consisted of notes with frequencies in the range of the of the fundamental frequency (*f*0) of the following speech, not its formants. Thus, it is possible that issues of acoustic continuity, rather than speech-specific processing, were responsible for the lack of rate dependence.

It seems reasonable, therefore, to resurrect the melodic precursor paradigm in examining possible non-speech effects on categorization of speech along a temporal dimension, providing that the precursor stimuli possess acoustic characteristics well-matched to the acoustic properties of the targeted speech contrast. The present experiments examine the extent to which sequences of precursor tones sharing spectral and temporal properties with following formant transitions can affect the stop-continuant perceptual boundary between initial [b] and [w] consonants in phonetic categorization.

Additionally, goodness judgments of [w] segments were elicited in these same contexts to observe the nature of any effects with respect to overall category structure.

Experiment 1

The purpose of Experiment 1 was to determine whether sequences of pure tones comparable in duration and frequency to following formant transitions affect speech categorization along a series of stimuli varying perceptually from [ba]-[wa]. Also of interest was whether tones in the range of a particular formant (F1 vs. F2, for which transition rate varies across speech stimuli) would produce superior effects.

Method

Participants

Thirty-four listeners participated, with half assigned to one condition and half to another in an arbitrary manner. Participants were college-age native English speakers with no known or obvious speaking or hearing disorders. Participants received undergraduate Psychology course credit for participation.

Stimuli

Stimuli were synthetic syllables from a [ba]-[wa] continuum preceded by pure tone sequences. Stimuli sampling the [ba]-[wa] continuum were modeled after intermediate-length stimuli used in the acoustically simplest (least ‘natural’) conditions of previous studies by Shinn and collaborators (Shinn & Blumstein, 1984; Shinn et al., 1985). Syllables were generated at 11.025 kHz using the HLsyn (Sensimetrics Corporation) implementation of the Klatt (1980) speech synthesizer’s cascade branch. All syllables were 171 ms in total duration. The first and second formant resonances, respectively, were held constant at 234 and 616 Hz for 40 ms before rising linearly to 769

and 1232 Hz. Continuum members varied only in length of F1 and F2 transitions; this duration was varied from 15 to 65 ms in 11 5-ms increments. The fundamental and third and fourth formant frequencies were held constant at 115, 2862, and 3500 Hz, respectively, for the entire duration of a syllable. Amplitude of voicing (AV) rose from 0 to 60 dB SPL during syllables' initial 5 ms and decreased to zero over the final 5 ms. Formant bandwidths for F1-F4 were 200, 90, 150, and 250 Hz, respectively. All remaining synthesis parameters were held constant at default values across continuum members. Following synthesis, stimuli were inspected in spectral and temporal dimensions (Matlab; Mathworks, Inc.) and found to be in close accord with synthesizer parameters. In particular, formant transition duration was observed to vary uniformly from 15 to 65 ms across the continuum. Finally, continuum members were equalized for RMS amplitude.

Precursor stimuli were designed to approximate the length of a short carrier sentence and to be spectrally and temporally matched with the acoustic characteristics of the initial formant transitions of the target syllables while remaining acoustically simple and unambiguously non-speech in nature. Each precursor was composed of a 1.2 s sequence of sine wave tones with frequencies sampled randomly from either the entire F1-F2 frequency range (Condition 1; 234 – 1232 Hz) or only the F2 range (Condition 2; 769 – 1232 Hz) of the following syllable. Each stimulus in the experiment possessed a unique random sampling of tone frequencies, so the frequency ranges of each condition were well represented within and across precursor stimuli. Sequences consisted entirely of either short or long tones. Fast sequences were made up of 30 short tones with onset-to-onset intervals of 40 ms (a duration 15 ms shorter than the 55-ms onset- plus-transition

duration of the most [ba]-like target syllable). Slow sequences were made up of 10 long tones with onsets separated by 120 ms (a duration 15 ms longer than the 105-ms duration of the most [wa]-like target). To ensure that precursors were perceived as sequences of tones rather than a continuous stream, a short silent gap was added to separate tones in time. The duration of this gap was 10 ms for both fast and slow sequences and provided an audible segmentation while also allowing tones' periodicity be clearly perceived. A "tonal event" in fast sequences, then, consisted of a 30 ms tone followed by a 10 ms silent interval; slow-sequence tonal events were made up of a 110 ms tone and a 10 ms silent gap. All tones had 5 ms onset and offset amplitude ramps. Target syllables were appended to the sequences following the final 10 ms silent gap.

Twenty fast and 20 slow sequences (each with a different sampling of tone frequencies) were randomly generated and paired with each [ba]-[wa] continuum member, resulting in 440 different stimuli. RMS amplitude of each tone sequence was normalized to that of the following syllable. Representative waveforms of fast and slow stimulus types for Experiment 1 are shown in the top panel of Figure 1.

Figure 1 about here

Procedure

Participants heard stimuli from either Condition 1 or Condition 2 in a single session. Acoustic presentation was under the control of Tucker Davis Technologies (TDT) System II hardware; stimuli were converted from digital to analog, low-pass filtered at 4.8 kHz, amplified and presented diotically over linear headphones (Beyer DT-150) at approximately 70 dB SPL(A) to participants seated in sound-attenuated booths.

Participants were instructed to listen to the entire sequence and respond whether the syllable most resembled ‘ba’ or ‘wa’ by pressing labeled response buttons.

Results

Responses for both conditions are shown in the top panel of Figure 2. A repeated measures ANOVA of probit-defined boundary locations (Finney, 1971) showed a significant shift of the [b]-[w] boundary in the direction of shorter transition durations (more [wa] responses) for syllables preceded by fast sequences compared to slow sequences, in both Condition 1, $F(1, 16) = 12.81$, $p = .003$, and Condition 2, $F(1, 16) = 13.55$, $p = .002$. This is the same direction as the speaking rate effects commonly observed in speech production (Miller & Baer, 1983) and perception (Miller & Liberman, 1979). A mixed model ANOVA comparing the categorization patterns produced by the different range of tone frequencies in Conditions 1 and 2 revealed a significant effect of tone duration, $F(1, 32) = 25.83$, $p < .001$, but no effect of tone frequency range, $F(1, 32) = .341$, $p = .564$, and no range × duration interaction, $F(1, 32) = .32$, $p = .575$. Thus, a similar small but reliable effect of precursor tone rate was observed whether tone frequencies sampled the F1-F2 range or only the F1 range. This suggests that if Summerfield’s (1981) failure to observe such an effect was due to lack of spectral continuity, such continuity may be obtained by aligning non-speech precursors’ frequency with that of either of the following formants (F1 or F2) with transition lengths contributing to the temporal distinction.

Figure 2 about here

The non-speech tone precursors possessed no information about articulatory gestures, so these findings present immediate problems for an account of rate effects that

depends on the recovery of articulatory events. The results are consistent with a durational contrast account. Nevertheless, it was not the case that the fast and slow tone sequences of Experiment 1 differed *only* in duration. Since identical inter-tone silent intervals and on-off ramps were used for both tone types and RMS amplitude was normalized across the entire precursor sequence, it can be seen in Figure 1 that individual fast (short) tones were somewhat greater in maximum amplitude than individual slow tones, compensating for the larger numbers of ramps and silent intervals. Thus, although fast and slow precursor sequences carried the same amount of total power, the maximum intensity level of individual short tone waveforms was approximately 1.22 times that of individual long tones, a 0.8 dB difference in sound level. As a result, fast sequences possessed slightly more power than slow sequences across the 30 ms period preceding the last silent interval before a target syllable. It is unlikely that a short term peripheral process such as forward masking operating on such a fast time scale could result in the categorization differences observed in Experiment 1 (e.g., Moore & Glasberg, 1983). However, it is necessary to remove any confounds potentially produced by differences in maximum or overall amplitude across precursors in determining whether differences in [b]-[w] perception resulted from non-speech precursor rate.

Experiment 2

Experiment 2 was designed to address this issue, examining whether it was indeed the rate of the precursor tones that caused the observed context effects in Experiment 1 rather than the precursors' amplitude characteristics. In one condition, the absolute maximum amplitude of precursor sequences, rather than the overall RMS amplitude, was held constant across tone types. In another condition, the amplitude envelope of tones

was also held constant, creating amplitude envelopes that were virtually flat with near-continuous tones in both conditions.

Method

Participants

Participants were 24 college-age native English speakers with no known or obvious speaking or hearing disorders. Participants received undergraduate Psychology course credit for their participation.

Stimuli

As in Experiment 1, stimuli were synthetic syllables from a [ba]-[wa] continuum preceded by pure tone sequences. Syllables were identical to those used in Experiment 1; tone sequences were identical in frequency composition and tone-to-tone interval to those in Experiment 1 Condition 2, differing only in tone amplitude and inter-tone silent interval duration. In two conditions, steady-state portions of individual tones, rather than entire precursor sequences including on-off ramps and silent intervals, were adjusted to the RMS amplitude of the following syllable, effectively normalizing the maximum amplitude of sequences across precursor rates. In Condition 1, this was accomplished by elongating individual tones to eliminate silent intervals completely and adding 5ms on-off ramps only after individual tone amplitudes were adjusted, resulting in a steady stream of connected tone events. Thus, overall sequences of fast (40 ms) tones possessed slightly less energy overall but had the same maximum amplitude as sequences of slow (120 ms) tones. This was more extremely the case in Condition 2, which had tone-ramp-silence composition identical to that of Experiment 1's Condition 2 but with tone sequences normalized for maximum, rather than overall, RMS amplitude. Representative

waveforms of stimuli for these conditions are shown in the second and third rows of Figure 1. Number, composition, and randomization of stimulus types within tests were identical to Experiment 1.

Procedure

Fifteen arbitrarily-selected participants heard stimuli from Condition 1 in a single session; a subset of 7 of these same participants and the remaining 9 participants heard Condition 2 stimuli. Procedures and apparatus were identical to Experiment 1. Participants were instructed to listen to an entire sequence and respond whether the syllable resembled ‘ba’ or ‘wa’ using response buttons.

Results

Data from two participants (one from Condition 1, one from Condition 2) were discarded for failing to reflect a reliable stop-continuant distinction based on formant transition (probit-defined boundaries were outside the limits of the continuum). Responses for the remaining tests are shown in the middle panel of Figure 2. As in Experiment 1, a repeated measures ANOVA of probit-defined boundaries revealed a significant shift in the [b]-[w] boundary in the direction of shorter transition durations for syllables preceded by fast sequences (more [wa] responses) compared to slow sequences, in both Condition 1, $F(1, 13) = 9.8$, $p = .008$, and Condition 2, $F(1, 14) = 15.5$, $p = .001$. Taken with the results of Experiment 1, this indicates that the *rate* at which tones occur in a precursor sequence effects perception of a following consonant, regardless of small differences in RMS amplitude, maximum amplitude, or amplitude envelope across sequence types.

Experiment 3

A final experiment was designed to determine whether non-speech precursors affect the entire category structure of a speech sound, as speech precursors do (Miller et al., 1997; Wayland et al., 1994), or whether non-speech effects are limited to the ambiguous stop-glide boundary region. Specifically, goodness ratings for the category [w] were obtained as formant transitions similar to those described in Experiments 1-2 increased in length from very short ([b]-like) to long ([w]-like) to exaggeratedly long ([*w], by Miller's notation). In designing this study, one concern was the recent suggestion (Utman, 1998) that shifts in category goodness curves as a function of apparent context rate do not properly reflect rate-dependent processing and, instead, are a product of the experimental design used by Miller and colleagues. Using natural voiced and voiceless consonants produced at various speaking rates as stimuli, Utman elicited category goodness ratings for voiceless consonants at these different rates. The expected dependence on speaking rate was observed only when participants were provided explicit instructions and prior exposure to tokens labeled voiced, voiceless, or "exaggerated, breathy versions" (this training provided even more familiarization than previous experiments by Miller et al.), and not when such training was absent. To address this question, the present experiment took an intermediate approach to pre-test training; participants were given no prior exposure to the [ba]-[wa]-[*wa] continuum members they would encounter during the experiment but were verbally informed of the types of productions they might expect to hear.

Method

Participants

Participants were 30 college-age native English speakers with no known or obvious speaking or hearing disorders. Participants received undergraduate Psychology course credit for participation.

Stimuli

Stimuli were synthetic syllables from a [ba]-[wa]-[*wa] (exaggerated [wa]) continuum preceded by tone sequences. Syllables were modeled after those of Experiments 1-2, except that it was necessary to increase syllable length to 200 ms to create transition durations yielding a sufficiently exaggerated [*wa] percept. Fundamental and formant values were identical to those of the previous three experiments; F1 and F2 transition durations were varied across the continuum from 15 ms to 160 ms in 30 5-ms steps. Precursor tone sequences were generated in the same manner as those of Experiment 2, Condition 2. Eight fast and eight slow precursor sequences were created for each continuum member, for a total of 480 different stimuli.

Procedure

Participants heard stimuli in sound-attenuated booths over headphones at approximately 70 dB SPL. They were instructed to listen to an entire sequence and then to decide how well the syllable resembled the syllable ‘wa’ as it occurs in English words. Participants were not given any explicit training or exposure to the speech stimuli before testing, but were told that some syllables should sound very much like ‘wa’ while others might sound more like ‘oo-a’, ‘ba’, ‘ma’, or some sound that isn’t used in English at all. For each sound, they were instructed to use a mouse to click somewhere along a sliding scale that appeared on the screen with the labels *not WA*, *ok WA*, and *good WA* positioned to its left, center, and right. Stimuli were presented in random order using *ALVIN*, a

software system recently developed by Hillenbrand and Gayvert (in press). The response scale was quantized to 1000 equally-spaced points; participants were instructed to make full use of the scale and could move a sliding cursor as desired before clicking a button labeled “OK” to register the selected rating and proceed to the next stimulus. Response patterns suggested that this two-step task resulted in at least two types of questionable responses. Participants would occasionally either (1) accidentally click the “OK” button before adjusting the *WA* rating scale, registering the same rating to two consecutive stimuli or (2) take excessive time adjusting the scale, disrupting the pace of stimulus presentation. Although these problems did not affect results qualitatively, it was determined that excluding those responses corresponding to each participant’s shortest and longest 5% (24 trials) of reaction times from consideration provided a more accurate representation of participant ratings.

Results

Overall response patterns are shown in the left panel of Figure 3. Following Wayland et al. (1994), the stimulus to which a participant assigned the highest mean *WA* rating for a given condition was taken as the participant’s best [w] exemplar for the condition. These peak locations are shown as the isolated data points labeled “Fast Peak” and “Slow Peak” in Figure 3. A repeated measures ANOVA revealed that the formant transition corresponding to the best [w] exemplar depended on precursor rate, $F(1, 29) = 8.01$, $p = .008$, in the expected direction. The best stimulus corresponding to the best [w] exemplar was 13.2 ms longer, on average, with slow precursors than with fast precursors. This strongly indicates that perception of the transition durations across the continuum, and not just near the perceptually-ambiguous boundary, was influenced by the precursor

tones such that they were perceived as longer following faster precursors. Thus, non-speech precursors affected the internal perceptual structure of the [w] category in the same way context speaking rate does, causing not only category boundaries but also the category best-exemplar to shift in a contrastive direction. This effect does not appear to be due merely to specific task characteristics, because (following the caution of Utman, 1998) explicit training on typical [b], [w], and [*w] tokens was not provided. Rather, it suggests that differences between Utman's results and previous findings may be due to other factors, including the naturalness of tokens (*cf.* Shinn et al., 1985) and the distribution of VOT.

Figure 3 about here

Lack of explicit training in the present study does seem to have resulted in considerable cross-participant variability in responses to the extended transition-length continuum. As shown in Figure 3, participants were generally reluctant to assign exaggerated [*wa] tokens ratings as low as those they gave [ba]-like tokens. This trend varied substantially from listener to listener, resulting in the large standard errors at longer transitions seen in Figure 3. Some participants demonstrated a precipitous decline in *WA* rating at very long durations, whereas others reached a plateau at some intermediate value or increased across the entire continuum. As a result, the variability in Figure 3 prohibits clear examination of patterns in category structure other than peak locations.

Therefore, to facilitate comparison of category structures across precursor types, an additional analysis following the methods of Wayland et al. (1994) considered only the responses of only those participants who demonstrated the expected decline in *WA*

rating for the exaggeratedly-long transitions. The criterion for demonstrating this decline was whether a participant assigned an average rating for the two longest transition lengths that was less than 90% of the highest rating they assigned to any continuum member (i.e. the peak *WA* rating) in the relevant precursor condition. Twenty of the 30 participants met this criterion. The right panel of Figure 3 shows the response curves for these participants, with absolute rating values smoothed over 5 consecutive duration points to mitigate additional variability due to the thousand-point scale and relatively small number of responses to each stimulus. Here the effects of non-speech precursors can be seen more clearly to resemble those of surrounding precursor rate, with a systematic rise and fall in category goodness occurring at roughly 10-15 ms longer transition durations for slow precursors than fast precursors. It can also be seen that participants' average absolute peak *WA* locations across conditions correspond well to the peaks in the overall rating functions, verifying that this is indeed an accurate measure for quantifying differences in category structure as a function of precursor rate.

In summary, non-speech precursors affected the perceptual [w] category in the same way context speaking rate does (Miller et al., 1997), in that category best-exemplar locations shifted in a contrastive direction based on precursor rate. Another measure often used by Miller and colleagues to represent category structure has been the size and orientation of a best-exemplar range surrounding this peak location, typically the estimated range (Miller & Volaitis, 1989a) of stimuli on either side of the absolute peak for which listeners assign an average rating at least 90% of that assigned to the peak stimulus. Although variability due to the task (described above) precluded estimation of similar ranges for participants in the present study, the smoothed data in Figure 3 (right)

suggest that this entire range of ratings was in fact shifted based on non-speech precursor rate.

General Discussion

The results reported here demonstrate that simple sequences of pure tones, selected to provide continuity with formant transitions in following speech, are sufficient to bring about rate effects on speech categorization remarkably similar to previously observed effects of speaking rate context. For a speech contrast differentiated entirely by the length of initial formant transitions, the perceived category boundary between the stop [b] and the continuant [w] shifted reliably depending on the rate of tones occurring in preceding sequences, in the same direction as it has been shown to for speaking rate (Miller and Liberman, 1979). The boundary consistently shifted in the direction of shorter transition durations (more [wa] responses) for syllables preceded by fast sequences compared to slow sequences, whether tones occurred in the entire F1-F2 or only the F2 frequency range (Experiment 1), and regardless of their overall amplitude or amplitude envelope (Experiment 2). Perhaps most convincingly, these effects penetrated the [w] category to affect its entire graded structure (Experiment 3). The best [w] exemplar, and probably the best-exemplar range along the transition-duration dimension, was shifted in a manner analogous to that previously observed for rate-varying speech context (Wayland et al., 1994; Miller et al., 1997). Taken together, these findings suggest that the apparent dependence on speaking rate in human perception of temporal speech cues need not rely entirely on a mechanism that is in any sense speech-specific. Since it is unlikely that perception of pure tone sequences is mediated by knowledge of speech categories or

their articulations or their direct recovery, a more general mechanism such as durational contrast must have been responsible for the results observed here.

Although it is not feasible to predict ‘optimal’ rate-dependent [b]-[w] perceptual category boundaries based on non-speech precursor rate like those derived from measurements of speech production (Miller and Baer, 1983), the difference between the size of the category boundary shift observed in the present experiments (1-2 ms for Experiments 1-2, 10-15 ms for Experiment 3) and the actual acoustic difference in tone lengths across conditions (80 ms between tones of Fast and Slow precurors) is striking. Figure 4 compares perceptual shifts observed in the present experiments and those of previous studies using speech precursor sequences (Summerfield, 1981; Wayland et al., 1994).

No reliable differences in effect sizes were observed between Experiments 1-2; the effects were, however, all generally smaller than those observed previously for speech precursors. As shown on the left of Figure 4, Summerfield (1981) observed a much larger shift in the [b]-[p] boundary when the rate of speech immediately preceding a target segment was manipulated. However, Summerfield did observe smaller effects when the rate-providing speech was displaced in time from the target. When the duration of the word “Why” instead of the word “you” in the precursor phrase “Why are you…” was manipulated, the observed rate effects on the target were more similar to those observed for non-speech precursors in the present experiments. Thus, one reason for the small category-boundary shifts in the present study may have been the long temporal window across which non-speech rate information was presented.

Figure 4 about here

Another cause for the small effect sizes may have been insufficient acoustic continuity between non-speech precursors and syllables, despite control of the rate and frequency characteristics of the precursors. It is likely that periodic, spectral, and spatial continuity are all important in achieving integration (and, presumably, providing for contrast) across sequential acoustic events (e.g., Bregman, 1990). The present pure tone precursor stimuli offered no periodic and only partial (single frequency band) spectral continuity with following syllables. In addition, the effectiveness of pure tones as precursors in general might well be questioned from a neuroethological standpoint, on the grounds that they insufficiently resemble the complex harmonic structures the auditory system has developed to perceive (see Eggermont, 2001; Lewicki, 2002 for review). The present stimuli were chosen solely for their unambiguously non-speech nature; it will be important to determine whether manipulations to the continuity of precursors or their naturalness change the extent of their perceptual influence on speech categorization.

Task differences may also be important in assessing effects of the rate of context stimuli, whether speech or non-speech. The effect size observed in Experiment 3, for which category goodness ratings were measured, was considerably greater than that observed in Experiments 1-2, for which categorization boundaries were estimated. This difference is akin to that observed for speech categories. In a similar category-goodness task, Wayland et al. (1994) observed larger effects of sentence rate on the best [p] exemplar ratings than the effect sizes observed by Summerfield (1981) for [b]-[p] category boundary shifts. The target stimuli used may also have influenced the size and nature of the observed effects. Acoustically simple synthetic syllables differing only in transition duration were used to encourage [b]-[w] identification along a purely temporal

dimension. Had additional cues to the two segments been present, either in more complex synthetic syllables or in natural speech, it is possible that non-speech rate effects would have diminished as speech effects seem to (Shinn & Blumstein, 1984; Shinn et al., 1985). It is even possible the unnatural quality of the stimuli made them more continuous acoustically with the simple non-speech precursors, further facilitating the observed effects. However, since the experiments demonstrate that non-speech rate is taken into account under these simplistic conditions, and since speaking rate effects emerge in noisier listening conditions even for very realistic stimuli (Miller & Wayland, 1993), it seems that effects of the type observed could play a role in natural speaking situations. Effects of non-speech precursors on perception of stimuli derived from natural speech have been demonstrated previously (e.g., Holt, in press). Additional experimentation will be needed to explore these possibilities.

Finally, it remains possible that the general contrastive effect demonstrated in the present study represents only one of multiple factors contributing to the rate-dependent nature of speech perception. One additional factor may well be speech- or language-specific knowledge. For individual speakers, dialects, and languages and for human speech sounds in general, there exists a multitude of highly predictable, and therefore presumably learnable, patterns (e.g., Miller, 1981) whereby the temporal properties of various speech segments co-vary with those of nearby segments. Contrastive effects generally work in the direction of perceptually mitigating rate-dependent variability. They exaggerate the differences between a given sound and its acoustic context, making it perceptually more distinct from those sounds with which it is coarticulated and therefore more like a prototypical example of a given category. A given formant

transition, for example, will sound shorter and therefore more [b]-like the longer the surrounding segments. However, since this effect bears no functional relation to context dependence in production, it is unlikely to result in perfect perceptual compensation for every contrast in every language. It seems likely, then, that language users compensate for any remaining variability by learning the rate-dependent covariance patterns specific to various contrasts. Additional research, perhaps involving cross-linguistic comparison of non-speech precursor effects, will be needed to determine how linguistic knowledge and contrast effects work together to accommodate perception. Beddor, Harnsberger, and Lindemann (2002), for example, observe language-specific patterns in apparent perceptual compensation for vowel coarticulation, citing differences between English and Shona speakers' category boundary shifts depending on the position of context-providing vowels. Comparison of such differences with analogous cross-linguistic observation of perceptual dependence on non-speech contexts will be informative in identifying the mechanisms responsible for context-dependent speech perception.

A final issue is the distinction between *rate* and *duration* as the concepts are presented in this and similar studies. It appears that transition duration, and not rate, provides the primary temporal cue to the stop-continuant contrast (Schwab, Sawusch, & Nusbaum, 1981), so it seems reasonable that preceding temporal information would affect the distinction by means of durational contrast (e.g., Goldstone et al., 1959; Goldstone et al., 1957; Walker & Irion, 1979; Walker et al., 1981). However, the precursor sequences in the experiments described here varied in both the duration and presentation rate of tones, creating a possible confound in this respect. The present study, therefore, does not rule out the possibility that a general compensation for precursor rate

(such as a non-speech-specific extrinsic timing mechanism), and not durational contrast, was responsible for the effects observed.

In conclusion, the present results demonstrate that the temporal properties of non-speech precursor sequences influence the perception of temporal speech contrasts in a manner parallel to previously-observed effects of speaking rate. Across experimental manipulations, the durations of pure tones were found to affect perception of formant transition durations in following syllables, as evidenced by shifts in both the stop-continuant, [b]-[w], category boundary and the overall graded structure of a the [w] category. This is taken to suggest that a general auditory effect such as durational contrast may play a role in the apparent rate-dependent nature of speech perception.

Author Note

Travis Wade and Lori L. Holt, Department of Psychology and Center for the Neural Basis of Cognition, Carnegie Mellon University.

This work was supported by a James S. McDonnell Foundation award for Bridging Mind, Brain, and Behavior to LLH, NIH grant 5 RO1 DC04674-02 to LLH, and by a fellowship from the NIH Postdoctoral Training Grant on “Individual Differences in Cognition.” The authors thank Christi Adams and Ashley Episcopo for help in conducting the experiments.

Correspondence concerning this article should be addressed to Travis Wade, twade@andrew.cmu.edu.

References

Ainsworth, W. A. (1974). The influence of precursive sequences on the perception of synthesized vowels. *Language and Speech, 17*, 103-109.

Allen, J., & Miller, J. (2001). Contextual influences on the internal structure of phonetic categories: A distinction between lexical status and speaking rate. *Perception & Psychophysics, 63*, 798-810.

Beddor, P. S., Harnsberger, J. D., & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: acoustic structures and their perceptual correlates. *Journal of Phonetics, 30*, 591-627.

Bregman, A. S. (1990). *Auditory Scene Analysis*. Cambridge, MA: MIT Press.

Cathcart, E. P., & Dawson, S. (1928). Persistence: A characteristic of remembering. *British Journal of Psychology, 18*, 262-275.

Dent, M. L., Brittan-Powell, E. F., Dooling, R. J., & Pierce, A. (1997). Perception of synthetic /ba/-/wa/ speech continuum by budgerigars (*Melopsittacus undulatus*). *Journal of the Acoustical Society of America, 102*, 1891-1897.

Diehl, R. L., & Walsh, M. A. (1989). An auditory basis for the stimulus-length effect in the perception of stops and glides. *Journal of the Acoustical Society of America, 85*, 2154-2164.

Eggermont, J. J. (2001). Between sound and perception: Reviewing the search for a neural code. *Hearing Research, 157*, 1-42.

Eimas, P. D., & Miller, J. L. (1980). Discrimination of information for manner of articulation by young infants. *Infant Behavior & Development, 3*, 367-375.

Finney, D. J. (1971). *Probit Analysis*. Cambridge: Cambridge University Press.

Fowler, C. A. (1980). Coarticulation and theories of extrinsic timing. *Journal of Phonetics, 8,* 113-133.

Fowler, C. A. (1990). Sound-producing sources as objects of perception: Rate normalization and nonspeech perception. *Journal of Acoustical Society of America, 88,* 1236-1249.

Fowler, C. A. (1992). Vowel duration and closure duration in voiced and unvoiced stops: There are no contrast effects here. *Journal of Phonetics, 20,* 143-165.

Fowler, C. A., Brown, J. M., & Mann, V. A. (2000). Contrast effects do not underlie effects of preceding liquids on stop-consonant identification by humans. *Journal of Experimental Psychology: Human Perception & Performance, 26,* 877-888.

Fujisaki, H., Nakamura, K., & Imoto, T. (1975). Auditory perception of duration of speech and non-speech stimuli. In G. F. a. M. Tatham (Ed.), *Auditory Analysis and Perception of Speech.* London: Academic Press.

Gay, T. (1978). Effect of speaking rate on vowel formant movements. *Journal of the Acoustical Society of America, 63,* 223-230.

Goldstone, S., Boardman, W. K., & Lhamon, W. T. (1959). Intersensory comparisons of temporal judgments. *Journal of Experimental Psychology, 57,* 243-248.

Goldstone, S., Lhamon, W. T., & Boardman, W. K. (1957). The time sense: Anchor effects and apparent duration. *Journal of Psychology, 44,* 145-153.

Gordon, P. (1988). Induction of rate-dependent processing by coarse-grained aspects of speech. *Perception & Psychophysics, 43,* 137-146.

Grossberg, S., Boardman, I., & Cohen, M. (1997). Neural dynamics of variable-rate speech categorization. *Journal of Experimental Psychology, 23,* 481-503.

Hillenbrand, J. M., & Gayvert, R. A. (in press). Open source software for experiment design and control. *Journal of Speech, Language, and Hearing Research*.

Holt, L. L. (in press). Temporally non-adjacent non-linguistic sounds affect speech categorization. *Psychological Science*.

Holt, L. L., & Kluender, K. R. (2000). General auditory processes contribute to perceptual accommodation of coarticulation. *Phonetica, 57*, 170-180.

Holt, L. L., & Lotto, A. J. (2002). Behavioral examinations of the level of auditory processing of speech context effects. *Hearing Research, 167*, 156-169.

Kidd, G. (1989). Articulatory-rate context effects in phoneme identification. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 736-748.

Klatt, D. H. (1980). Software for a cascade/parallel formant synthesizer. *Journal of the Acoustical Society of America, 67*, 971-990.

Kluender, K. R., Coady, J. A., & Kiefte, M. (2003). Sensitivity to change in perception of speech. *Speech Communication, 41*, 59-69.

Lewicki, M. S. (2002). Efficient coding of natural sounds. *Nature Neuroscience, 5*, 356-363.

Lotto, A. J., & Kluender, K. R. (1998). General contrast effects of speech perception: Effect of preceding liquid on stop consonant identification. *Perception & Psychophysics, 60*, 602-619.

Lotto, A. J., Kluender, K. R., & Holt, L. L. (1997). Perceptual compensation for coarticulation by Japanese quail (*Coturnix coturnix japonica*). *Journal of the Acoustical Society of America, 102*, 1134-1140.

Lotto, A. J., Sullivan, S. C., & Holt, L. L. (2003). Central locus for nonspeech context effects on phonetic identification. *Journal of the Acoustical Society of America, 113*, 53-56.

Mack, M., & Blumstein, S. (1983). Further evidence of acoustic invariance in speech production: The stop-glide contrast. *Journal of the Acoustical Society of America, 73*, 1739-1750.

Miller, J. L. (1981). Effects of speaking rate on segmental distinctions. In P. D. Eimas & J. L. Miller (Eds.), *Perspectives on the Study of Speech*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Miller, J. L. (1987). Rate-dependent processing in speech perception. In A. Ellis (Ed.), *Progress in the Psychology of Language* (pp. 119-157). Hillsdale, NJ: Lawrence Erlbaum Associates.

Miller, J. L., & Baer, T. (1983). Some effects of speaking rate on the production of [b] and [w]. *Journal of the Acoustical Society of America, 73*, 1751-1755.

Miller, J. L., Green, K. P., & Reeves, A. (1986). Speaking rate and segments: A look at the relation between speech production and speech perception for the voicing contrast. *Phonetica, 43*, 106-115.

Miller, J. L., & Liberman, A. M. (1979). Some effects of later-occurring information on the perception of stop consonant and semivowel. *Perception & Psychophysics, 25*, 457-465.

Miller, J. L., O'Rourke, T. B., & Volaitis, L. E. (1997). Internal structure of phonetic categories: Effects of speaking rate. *Phonetica, 54*, 121-137.

Miller, J. L., & Volaitis, L. E. (1989a). Effect of speaking rate on the perceptual structure of a phonetic category. *Perception & Psychophysics, 46*, 505-512.

Miller, J. L., & Volaitis, L. E. (1989b). Internal structure of phonetic categories: Effects of speaking rate. *Phonetica, 54*, 121-137.

Miller, J. L., & Wayland, S. C. (1993). Limits on the limitations of context-conditioned effects in the perception of [b] and [w]. *Perception & Psychophysics, 54*, 205-210.

Moore, B. C. J., & Glasberg, B. R. (1983). Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *Journal of the Acoustical Society of America, 74*, 750-753.

Newman, R. S., & Sawusch, J. R. (1996). Perceptual normalization for speaking rate: Effects of temporal distance. *Perception & Psychophysics, 58*, 540-560.

Oller, D. K., Eilers, R. E., Miskiel, E. M., Burns, R., & Urbano, R. (1991). The stop/glide boundary shift: Modeling perceptual data. *Phonetica, 48*, 32-56.

Pickett, J., & Decker, L. (1960). Time factors in perception of a double consonant. *Language and Speech, 32*, 693-703.

Pind, J. (1995). Speaking rate, voice-onset time, and quantity: The search for higher-order invariants for two Icelandic speech cues. *Perception & Psychophysics, 57*, 291-304.

Pisoni, D. B., Carrell, T. D., & Gans, S. J. (1983). Perception of the duration of rapid spectrum changes in speech and nonspeech signals. *Perception & Psychophysics, 34*, 314-322.

Port, R. (1981). Linguistic timing factors in combination. *Journal of the Acoustical Society of America, 69*, 262-274.

Purves, D., & Lotto, R. D. (2002). *Why we see what we do: An empirical theory of vision*. Sunderland, MA: Sinauer Associates.

Schwab, E., Sawusch, J. R., & Nusbaum, H. C. (1981). The role of second formant transitions in the stop-semivowel distinction. *Perception & Psychophysics, 29*, 121-128.

Shinn, P., & Blumstein, S. (1984). On the role of the amplitude envelope for the perception of [b] and [w]. *Journal of the Acoustical Society of America, 75*, 1243-1252.

Shinn, P., Blumstein, S. E., & Jongman, A. (1985). Limitations of context conditioned effects in the perception of [b] and [w]. *Perception & Psychophysics, 38*, 397-407.

Sinnott, J. M., Brown, C. H., & Borneman, M. A. (1998). Effects of syllable duration on stop-glide identification in syllable-initial and syllable-final position by humans and monkeys. *Perception & Psychophysics, 60*, 1032-1043.

Summerfield, Q. (1975). Aerodynamics versus mechanics in the control of voicing onset in consonant-vowel syllables. In *Speech perception (no. 4)*. Belfast: Queen's University, Dept. of Psychology.

Summerfield, Q. (1981). Articulatory rate and perceptual constancy in phonetic perception. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1074-1095.

Utman, J. (1998). Effects of local speaking rate context on the perception of voice-onset time in initial stop consonants. *Journal of the Acoustical Society of America, 103*, 1640-1653.

Walker, J., & Irion, A. L. (1979). Two new contingent aftereffects: Perceived auditory duration contingent on pitch and on temporal order. *Perception & Psychophysics, 26*, 241-244.

Walker, J., Irion, A. L., & Gordon, D. S. (1981). Simple and contingent aftereffects of perceived duration in vision and audition. *Perception & Psychophysics, 29*, 475-486.

Wayland, S. C., Miller, J. L., & Volaitis, L. E. (1994). The influence of sentential speaking rate and the internal structure of phonetic categories. *Journal of the Acoustical Society of America, 95*, 2694-2701.

Figure Captions

Figure 1. Typical waveforms showing amplitude and duration characteristics of precursor sequences used in Experiments 1-2. The insets in the bottom left corner of each graph show an expanded view of the first 240 ms of the waveform.

Figure 2. Categorization responses from Experiments 1-2.

Figure 3. On the left, average [w] goodness ratings with standard error of the mean are plotted as a function of syllable transition duration. Listeners' average peak [w] ratings with Fast vs. Slow non-speech precursors are shown as the isolated symbols. For these symbols, the y-axis is arbitrary, but placement along the x-axis reveals a difference in the best-rated [w] exemplar along the transition duration dimension as a function of non-speech precursor rate. The right panel presents smoothed ratings and peak locations for 20 participants whose ratings decreased to 90% of peak level at the longest transition duration values.

Figure 4. Comparison of the effect sizes (in ms of boundary shift across conditions) produced by the present non-speech precursor rate manipulations and previous studies examining speech precursor rate by Summerfield (S, 1981) and Wayland et al. (WMV, 1994). Error bars for S are estimates from visual data.

FIGURE 1:

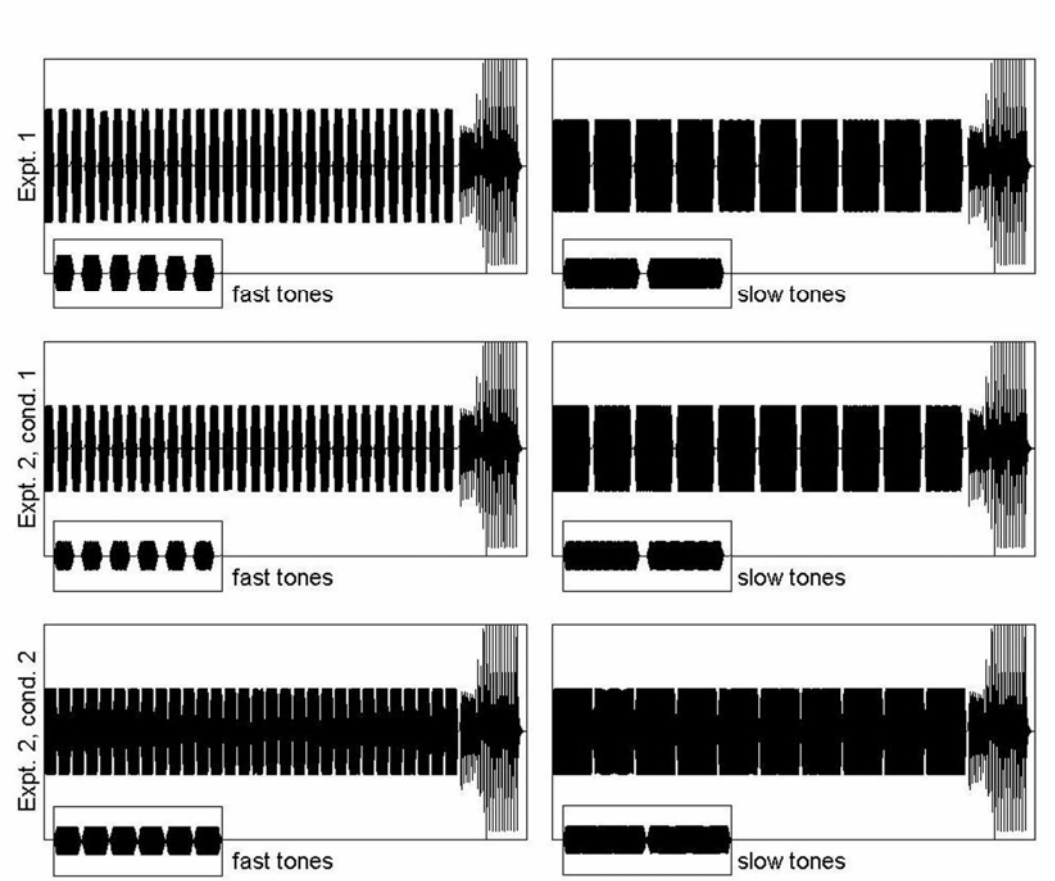

Expt. 1
fast tones
slow tones
Expt. 2, cond. 1
fast tones
slow tones
Expt. 2, cond. 2
fast tones
slow tones

FIGURE 2:

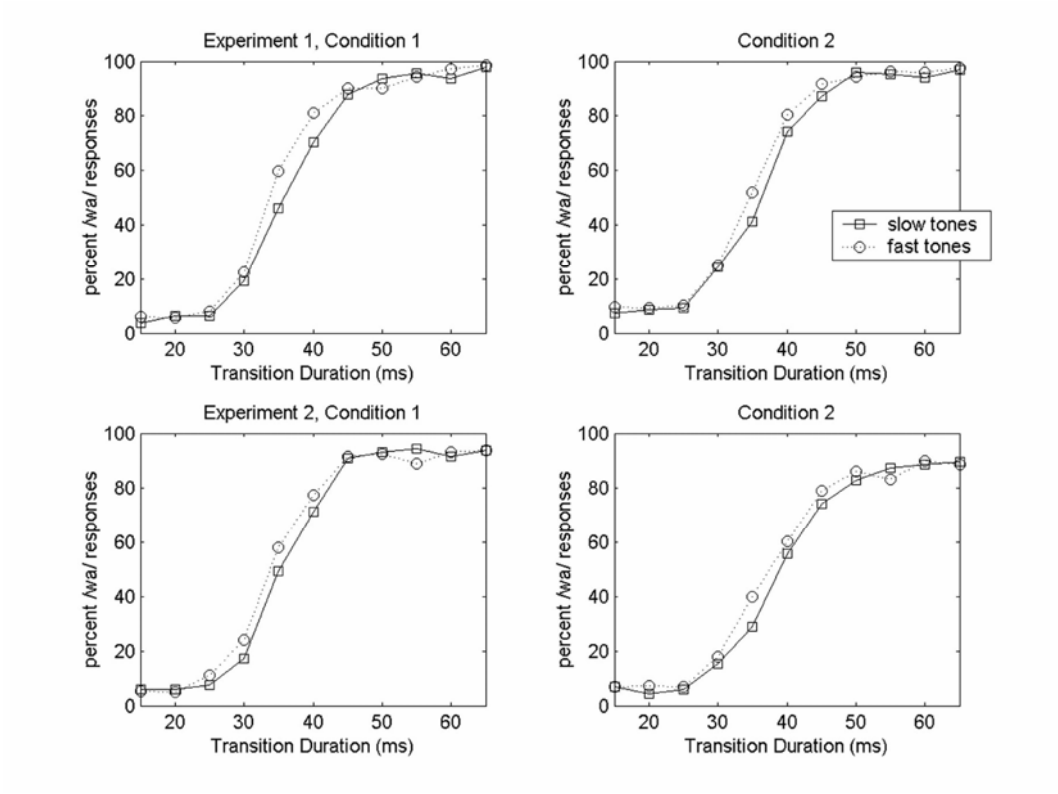

Experiment 1, Condition 1
Condition 2
Experiment 2, Condition 1
Condition 2
percent /wa/ responses
Transition Duration (ms)
slow tones
fast tones
0
20
40
60
80
100
20
30
40
50
60

FIGURE 3:

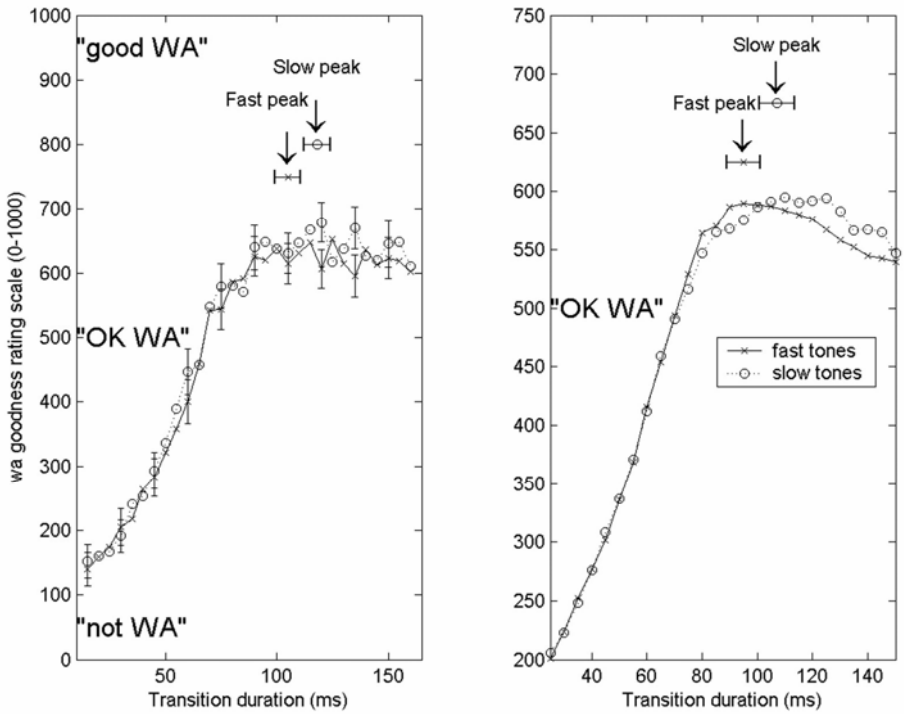
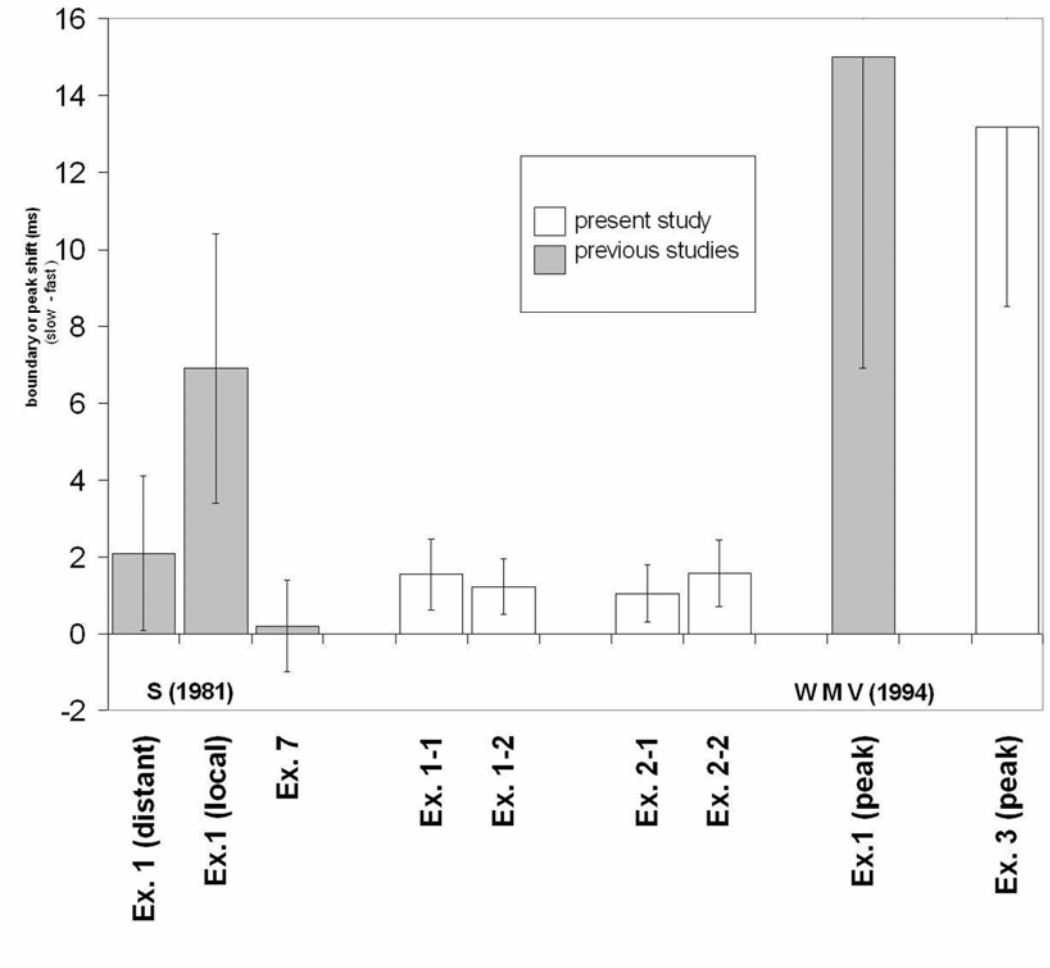

"good WA"
Slow peak
Fast peak
"OK WA"
"not WA"
wa goodness rating scale (0-1000)
Transition duration (ms)
Slow peak
Fast peak
"OK WA"
fast tones
slow tones
Transition duration (ms)

FIGURE 4:


16
14
12
10
8
6
4
2
0
-2
boundary or peak shift (ms)
(slow - fast)
present study
previous studies
S (1981)
W M V (1994)
Ex. 1 (distant)
Ex.1 (local)
Ex. 7
Ex. 1-1
Ex. 1-2
Ex. 2-1
Ex. 2-2
Ex.1 (peak)
Ex. 3 (peak)