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The effects of increasing consonant/vowel intensity ratio on speech loudness*

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Abstract—It was hypothesized that speech loudness may be primarily determined by the level of the vowel and that, as a consequence, high positive consonant/vowel intensity ratios (C/V ratios) could be tolerated by hearing-impaired listeners with possible improvement in intelligibility. The present study was concerned with the effects of high C/V ratios on the loudness of speech as a necessary first step prior to more detailed studies of loudness tolerance and intelligibility. Recordings of four CVC monosyllables were digitized and one of the consonants in each word was selected for amplification relative to a constant vowel level. For each word a set of seven tokens was prepared representing a range of C/V ratios from approximately -20 dB to 9 dB. The loudness of each token was obtained through a loudness matching task involving a standard word presented at 90 dB SPL. In addition, sets of nonspeech stimuli were created to approximate the C/V ratios represented in two of the monosyllables. Loudness of nonspeech tokens was obtained using the same loudness matching paradigm. It was found that high C/V ratios had no appreciable effect on speech loudness. (The nonspeech stimuli gave similar results, however, so it was not possible to conclude that speech was unique in that respect.) The findings in general are encouraging for the further study of the influence of C/V ratio on intelligibility and the eventual incorporation of C/V processing into digital hearing aids.

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INTRODUCTION

The digital hearing aid has the capability for advanced forms of signal-processing. One exciting possibility is that of incorporating speech enhancement algorithms in a digital hearing aid. Such algorithms would be designed to increase the intelligibility of speech beyond its natural level and make it more resistant to the distortions introduced by the user's hearing loss and to background noise. Consonants are generally much less intense than vowels (4) and it has been shown that increasing the consonant-to-vowel (C/V) intensity ratio increases intelligibility (9,23). More recently, it has been shown that increasing the C/V ratio improves intelligibility of speech for hearing-impaired individuals (8,15,16). These recent studies increased C/V ratio to near zero, i.e., the consonant levels were brought up to near the level of the associated vowel(s). Given the importance of consonant intelligibility to speech recognition by hearing-impaired persons (see Walden (20) for a thorough review), it is reasonable to ask whether more extreme positive C/V ratios can be tolerated and used beneficially by hearing-impaired listeners. The present study focuses on the tolerance question. That is, it is possible that while the positive C/V ratios may improve intelligibility for some hearing-impaired listeners, the listener would perceive the speech to be too loud for comfort when the vowels reach an optimal intensity near the discomfort level.

Background

The loudness of speech has been studied using several established paradigms. Researchers sought to determine whether speech perception was unique or merely a refined form of general auditory processing, and loudness provided fertile ground for debate. Early work was influenced by Stevens' power law and the sone scale (19). This method involved determining the relationship between subjective measures of loudness, such as magnitude estimation, and physical properties of the stimulus (usually overall SPL). The relationship is typically a power function whose exponent is determined by noting the slope of the function plotted on log-log coordinates.

Exponents in the range of 0.6 to 0.8 were generally found for nonspeech stimuli, although Pollack reported 0.4 in 1952 (18). Sometimes isolated vowels and speech yielded exponents in this range as well (11,22). However, there was a tendency for higher exponents for speech (0.8 to 1.2), especially when the subject was asked to produce changes in loudness in his own vocal production (12,21) rather than passively listening to electronically controlled stimuli. These studies generally focused on overall SPL as the physical correlate of loudness, with some notable exceptions (10).

More recently, additional physical properties of speech have been identified as contributing to speech loudness. Ladefoged and McKinney (10), Brandt, Ruder, and Shipp (2), Allen (1), Mendel, et al. (14), among others, have noted that perceived effort in speech influenced loudness. This was shown to be true in studies where effort and SPL were independently controlled (2,14). Presumably the special characteristics associated with high-effort (shouted) speech, such as additional harmonic energy in the high frequencies, were audible and influenced loudness judgment. Fundamental frequency and the specific vowels involved have also been studied as possible factors in speech loudness (5,13). These questions are typically studied using a loudness-matching task where the level of a pure tone or noise is adjusted until it is equal in loudness to a test stimulus. Differences in the SPL of the tone obviously reflect differences in the loudness of the stimuli.

The loudness of speech appears, then, to be influenced by special acoustic properties of the signal in addition to overall SPL. (Whether these findings are true for hearing-impaired listeners; and whether they hold true for stimuli presented at useful amplification levels of 90 dB SPL and higher, is not known.) At least to the extent that the acoustic properties of speech are unique, the sensation of loudness associated with speech is unique.

An additional property of speech loudness that is especially relevant to the present study is the fact that the loudness of speech resides almost entirely in the vowels. Though consonants may have to be present before the signal is processed as speech (10), they do not seem to influence the loudness (3,25). The overall SPL of running speech, for example, is seen to be a series of high-energy vowels modulated by lower energy consonant clusters at a rate of 3-5 cycles per second. The loudness of continuous speech, as indicated by adjusting the level of a pure tone to be equal in loudness, is essentially determined by the most intense stressed vowels (3,25). The consonant clusters do not exert any sort of "averaging" effect that would lower the level of the matching pure tone significantly below that of the vowels. Similar results are obtained wth amplitude-modulated white noise. When modulation in the range of 3 Hz is used (24,25) the matching tone is set to the level of the peak (i.e., maximum SPL) portion of the noise. Averaging effects occur, however, when the noise is modulated rapidly and a loudness match lying between the minimum and maximum SPL of the noise is obtained. It is not clear, then, whether the strong tendency to base speech loudness on the vowel is a special property of speech perception (and thus useful in the design of signal-processing hearing aids that would manipulate C/V ratio), or whether it is simply a property of the temporal pattern of SPL and would vanish when C/V ratios are equal to or greater than zero. The present study was designed to give preliminary answers to this question and to provide direction for additional research.

Rationale

The rationale for the study is: If the vowel really is the primary determinant of speech loudness (and presumably also of discomfort to a hearing-impaired listener), then it might be possible to maintain an optimal SPL vowel level while amplifying the consonants to above that level without causing discomfort. If consonants can be tolerated when their intensity is substantially above that of accompanying vowels, then it is feasible to investigate consonant intelligibility at positive C/V ratios.

The first step in this line of investigation was to determine the effect of C/V manipulation upon speech loudness. As noted above, the physical correlates of speech loudness and the possible differences of speech loudness from the loudness of nonspeech sounds are not well defined. It is necessary, then, to investigate also the effects on loudness of analogous manipulations of nonspeech auditory stimuli. Our working hypothesis was that artifically high positive C/V ratios would have minimal effect on the loudness of monosyllables, but that corresponding alterations of nonspeech sounds would influence loudness significantly.

METHOD

Overview

The speech stimuli consisted of monosyllabic CVC words in which one of the consonants was altered with computer-based waveform editing. For each word this yielded a set of seven tokens representing a wide range of C/V ratios. Subjects performed a loudness-matching task in which they varied the overall SPL of each token until it was equal in loudness to another (standard) word presented at a constant 90 dB SPL. The plots of C/V ratio (7 tokens per word) versus SPL of the standard, obtained through loudness matching, were then generated for each word and subject, and the shapes of the functions were examined. Slopes near zero would show no effect of altering C/V ratio, whereas positive slopes would indicate that increasing C/V ratio was associated with increasing loudness. An identical task was performed using as stimuli nonspeech tokens obtained by altering the envelopes of a 100 Hz square wave in ways designed to duplicate the temporal-amplitude characteristics of two of the words.

Subjects

Twenty hearing-impaired adults and 10 normal-hearing adults served as subjects. The normal-hearing subjects were health-care professionals in a large military hospital. The hearing-impaired subjects were active-duty military personnel enrolled in aural rehabilitation classes at the same hospital. All were new hearing aid users and exhibited bilateral high-frequency hearing loss typical of long-term noise exposure. (mean age = 42.1 yrs, SD = 15.0 yrs) **Table 1** shows the audiometric data for the 20 ears tested. All hearing-impaired subjects showed abnormal growth of loudness at 4000 Hz in the test ear. This was determined with a monaural loudness matching task using an 80 dB HL 500 Hz tone as the standard.

Table 1.
Mean audiometric data for test ear of 20 hearing-impaired subjects.

	Frequency (kHz)						
	.5	1.0	2.0	3.0	4.0	6.0	8.0
Mean	11.7	12.0	25.5	58.2	73.3	74.2	67.5
SD	11.0	8.9	18.0	14.8	9.2	15.5	16.6

Speech Stimuli

Four words were selected as the basis for the speech stimuli. High quality tape recordings of a male talker producing "seen", "gave", "thin", and "robe" were digitized at a sampling rate of 10 kHz with a resolution of 12 bits per sample. The resulting waveform files were then processed on a digital computer to yield tokens of each word with altered C/V ratios. Only one of the two consonants in each word was altered, as shown in **Table 2.**

Table 2.
Characteristics of speech and nonspeech stimuli. Location refers to whether initial (I) or final (F) segment was altered.

Stimulus	Overall duration (ms)	Duration of altered segment (ms)	Location	C/V or I/F Ratio (dB)
"Seen"	681	220	I	−18
"Gave"	550	132	F	−21
"Robe"	615	110	F	−18
"Thin"	420	176	I	−22
NS 1	681	220	I	−15
NS 2	550	120	I	−15

The alteration of any particular word was performed as follows. First, a moving 50-sample (5 ms) RMS averaging window passed through the waveform to yield a smoothed amplitude-time structure (envelope) of the word. The envelope and the original raw waveform were then displayed on a high-resolution interactive graphics system and the consonant-vowel boundary was located manually. The ratio in dB between the most intense section in the consonant portion of the waveform and the most intense section in the vowel portion was calculated as the initial (unaltered) C/V ratio. The initial C/V ratios and the durations of the consonant and vowel segments are listed in **Table 2.** The consonant portion of the waveform was then altered to achieve a specified C/V ratio and an appropriate smooth transition from consonant to vowel was produced. For each word, tokens were generated to have the following C/V ratios: 1) unaltered; 2) −6dB; 3) −3dB; 4) 0dB; 5) +3 dB; 6) +6 dB; and, 7) +9 dB. Thus a total of 28 tokens (4 words X 7 C/V ratios) were generated and stored as disk files. The tokens were identical to the original words except for the amplification of the consonant segment to the specific C/V ratios.

The word "laugh," produced by the same male talker, was selected as a standard for loudness-matching. A recording of "laugh" was digitized as described above, but no alteration of consonant intensity was performed. All five recordings had previously been adjusted to produce equal vowel levels that are based on the value of the maximum 50-point RMS segment average in the vowel prior to alteration.

Preparation of Speech Stimulus Tape

The basic stimulus unit for loudness matching consisted of the standard "laugh" followed by a token. These stimuli were always presented in series of 10 repetitions involving the same token. Thus the loudness value of any particular token was based on the subject hearing 10 repetitions of the basic unit (standard + token) and adjusting the level of the token to match the loudness of the standard over the course of the 10 presentations. A two-track audio tape containing the series (i.e., 10 repetitions) for each of the 28 tokens in random order was prepared by digital-to-analog conversion of the digitized files. The standard was recorded on track 1 and the token on track 2 of the tapes to allow track independent manipulation of the presentation levels. The standard and the token were separated by 250 ms and each instance of standard-plus-token in a series of 10 repetitions was separated from the next by approximately 3 seconds. Calibration tones and a series of 15 practice items were recorded at the beginning of the tape.

Nonspeech Stimuli

Two complex nonspeech stimuli (NS 1 and NS 2) were generated and then altered in ways directly analogous to the C/V ratio alterations performed on the speech stimuli. The stimuli were generated using a 100 Hz square wave, which was digitized and edited to yield two segments of predetermined lengths. NS 1 was modeled after the speech stimulus "seen" and was 681 ms in length. A point 220 ms into the waveform (corresponding to the /s/ − /i/ boundary) was located, and the square wave was then modulated in such a way that the initial 220 ms segment was 15 dB below the level of the remaining 461 ms; i.e., the ratio of the levels between initial and final segments (the I/F ratio) was − 15 dB. This signal was considered to be analogous to the original unaltered "seen". The file was then processed to yield six additional tokens with I/F ratios of −6 dB, −3 dB, 0 dB, +3 dB, +6 dB and +9 dB.

NS 2 was modeled after the speech stimulus "gave" and was 550 ms in length. An initial segment of 120 ms was reduced in level to correspond to the /g/ in "gave". Note that this is not strictly analagous to the speech stimulus, because in "gave", the final consonant was the one altered. The initial segment in NS 2 was selected, however, to allow a more direct estimate of the effects of length of altered segment in the nonspeech materials (220 ms in NS 1 vs. 120 ms in NS 2). A modulated square-wave signal was created whose initial 120 ms segment was 15 dB less than the final 430 ms segment. This waveform with an I/F ratio of −15 dB was then altered to produce six additional tokens with the same I/F ratios as NS 1. Note that in the nonspeech stimuli the two tokens with 0-dB I/F ratio (one in the NS 1 and one in the NS 2 set) represent waveforms that have been restored to a steady-state square wave with no envelope modulation.

Preparation of Nonspeech Stimulus Tape

The nonspeech stimulus tape was prepared in the same format as the speech stimulus tape: calibration tones, practice series of 15 basic units (standard followed by another reproduction of standard), then 14 token series in random order. Each token series contained 10 repetitions of the basic stimulus unit (standard followed by token). The standard in any particular series was either NS 1: 0 dB I/F or NS 2: 0 dB I/F, chosen to match the token.

Procedure

The stimulus tapes were played on a high fidelity, two-channel audio tape recorder. Line outputs were directed to speech and auxilliary inputs of a Grason-Stadler speech audiometer and from there to one of a pair of TDH-39 earphones. This arrangement allowed the level of the two channels of the tape (containing the standard and the token) to be calibrated and then controlled independently with the audiometer attenuators before the signals were combined into one earphone. Both channels were set so that a reading of 80 dB on their respective audiometer dials corresponded to an output level of the unaltered part of the stimulus in the earphone of 90 dB SPL as measured with a B&K sound level meter and 6 cc coupler (C scale, fast reading). For example, in the case of a nonspeech token with a positive I/F ratio such as NS 1: +6 dB, the initial part of the token was at 96 dB and the final part was at 90 dB SPL when the audiometer dial read 80 dB. Because the digitized speech files were equated for equal peak RMS on the waveforms of the unaltered words, there was some slight variation among the SPL of the four words (measured on the unaltered vowel portion) as played through the system and measured by the sound-level meter. This variation was on the order of 1 to 2 db and was removed by adjusting the subjects' responses *a posteriori*. This adjustment was minor in magnitude and had no effect on the slope of loudness function, since values for all tokens of any one word were adjusted by the same amount.

Subjects were tested individually in a sound-treated audiometric suite. Test ear was selected by the subject except for impaired subjects with a clear difference between ears. In that case, the poorer ear was selected. Hearing-impaired subjects were tested for abnormal growth of loudness in the test ear at 4 kHz with a monaural loudness balance test using 500 Hz at 80 dB HL as the standard. Loudness-matching data were obtained in the following manner: Subjects were seated near the console of the audiometer such that they could manipulate the attenuator dial without seeing the setting. They were instructed to adjust the dial until the loudness of the second word (or noise) in the pair was equal to the first. They were encouraged to make the variable item slightly louder and then softer than the standard and gradually "zero in" on an exact loudness match during the 10 repetitions of the standard + token. The dial reading was noted by the experimenter and the dial was reset randomly, either higher or lower, to provide a different starting point for the next token series. At the end of each of the two tapes, five additional token-series were presented a second time to assess reliability.

The 10 normal-hearing subjects heard the speech tape on one day and approximately 1 week later heard the nonspeech tape and a second playing of the first 15 token-series on the speech tape. The 20 hearing-impaired listeners were divided into two groups of 10 subjects. The first group heard only the speech tape; the second group heard the nonspeech tape and the first 15 token-series of the speech tape.

RESULTS

Monosyllables

The intent of the study was to determine if the progressive increase in C/V ratio across the tokens for a word produced a corresponding increase in loudness. To examine this question, the functions relating C/V ratio in dB to loudness level in dB were plotted for each word separately for each subject, and the slopes of the functions were calculated. Similar plots and calculations relating I/F ratio and loudness were obtained for the two nonspeech stimuli as well. Recall that a slope of 1.0 would indicate that for every dB increase in C/V or I/F ratio a corresponding increase of one dB in loudness occurred. A slope of zero on the other hand would mean that no consistent change in loudness had been observed.

The data on speech loudness obtained from the normal subjects and the group of hearing-impaired

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Table 3.
Mean slopes of loudness functions obtained for each word by normal and hearing-impaired listeners.

		"SEEN"	"GAVE"	"ROBE"	"THIN"	Group mean
Hearing-impaired						
(n = 10)	Mean	0.075	−0.025	−0.003	0.062	0.027
	SD	0.06	0.06	0.04	0.04	0.06
Normal-hearing						
(n = 10)	Mean	0.056	0.026	0.007	0.101	0.048
	SD	0.10	0.05	0.04	0.05	0.07
Overall mean		0.065	0.001	0.002	0.082	
	SD	0.08	0.06	0.04	0.05	

listeners who heard the speech stimuli were considered first. The mean slopes for each word and group are shown in **Table 3**. It may be seen that the slopes were near zero, with small standard deviations, confirming the impression obtained from listening to the tokens that the changes in C/V ratio had little effect on speech loudness. A two-factor ANOVA (factors were words and groups, with repeated measures on words) was performed on the slopes to determine if the means in **Table 3** differed significantly. The analysis, shown in **Table 4,** indicates that the group means did not differ significantly (0.027 vs. 0.048) nor did words and groups interact. The mean slopes of the words, however, did differ significantly at a probability less than 0.001. This is due to the small within-subject variance and is not interpreted as a meaningful difference. The largest mean slope was 0.08 for "thin" and the smallest was 0.001 for "gave", neither of which differs from zero by an amount that could even be seen on a graph, let alone be considered to be a meaningful increase in loudness with increasing consonant intensity.

Two factors that might have influenced this interpretation were considered. First, it it useful to point out that the mean slope of the loudness function for individuals is not equivalent mathematically to the slope of the mean loudness function derived from group data. Slopes based on mean loudness levels for each token were determined. These slopes were also found to be essentially zero. Consequently, the above-mentioned potential problem of nonequivalency was nonexistent in these data. Second, it is possible that loudness of speech is related to the most intense part of the word, regardless of whether it is a consonant or vowel. If this were true, then the loudness function would be flat through 0 dB C/V ratio and begin to rise as the consonant became more intense than the vowel. This would result in a fairly small slope overall. The slope in this case would not represent the function accurately, however, and would obscure meaningful effects at the positive C/V ratios. An examination of the individual plots revealed no tendencies for greater loudness at the positive C/V ratios. It appears that manipulation of C/V ratio does not increase loudness of monosyllables.

Table 4.
Analysis of variance for slope of loudness function. Factors are group (normal-hearing and hearing-impaired) and word (four words). Error terms are omitted.

Source	df	MS	F	p
Group	1	0.0084	1.56	.23
Word	3	0.0354	12.21	.0001*
Group X word	3	0.0050	1.73	.17

* $p < .05$

Nonspeech Stimuli

The same analysis procedure was applied to the loudness matching data from the tokens of the two non-speech stimuli, NS 1 and NS 2. The mean slope for NS 1 was 0.049 (SD = .07) and for NS 2 was 0.117 (SD = .07) while the mean slope SPL for the hearing-impaired subjects across stimuli was 0.10 and for the normal-hearing subjects was 0.06 (SD = .02 and 0.1 respectively). A two-factor ANOVA (factors were groups: hearing-impaired and normal,

Table 5.
Analysis of variance for slope of loudness function. Factors are group (normal-hearing and hearing-impaired) and nonspeech stimulus (NS 1 and NS 2). Error terms are omitted.

Source	df	MS	F	p
Group	1	0.0137	3.10	.09
NS stimulus	1	0.0467	8.72	.008*
Group X NS stim.	1	0.0033	0.61	.44

* $p < .05$

and nonspeech stimuli: NS 1 and NS 2, with repeated measures on stimuli) was performed and is shown in **Table 5.** It may be seen that the two stimuli differed significantly (P = .008) and the groups approached significance (P = .095). Given the approximate range of the slopes from 0.0 to 0.1 however, it is difficult to conclude that the statistical significance has any meaningful interpretation. Again, the alterations of I/F intensity ratio produced no meaningful change in loudness.

Reliability

Reliability was good, as seen in a test-retest correlation of 0.84 across the subjects, and in a mean test-retest difference in loudness of 1.1 dB.

DISCUSSION

The primary finding of the study was that even large increases in consonant/vowel intensity ratio in either the initial or final portion of a CVC monosyllable do not appreciably increase the loudness of the word. This finding was true for both normal hearing subjects and subjects with mild-to-moderate high-frequency sensorineural hearing loss. Also, the normal-hearing listeners and a second group of hearing-impaired listeners yielded the same flat loudness functions as had been obtained with speech when the stimuli were complex nonspeech sounds that duplicated closely the envelope characteristics of two of the words. Thus it is not clear that the phenomenon is due to the unique nature of speech. It may simply be a product of the somewhat shorter duration of the altered portion of the word or tone complex relative to the unaltered portion.

An answer, to whether the lack of increased loudness in positive C/V ratio tokens is related to the temporal proportion of the stimulus that is altered, could be obtained by increasing intensity of both initial and final consonant clusters in words like "sis" and "storms" where combined consonants are longer than the vowel.

There appeared to be no effect on loudness of the short versus long (120 ms vs. 220 ms) initial segment in the nonspeech stimuli. Both yielded near-zero slopes. The +6 dB and +9 dB tokens posed some problems for loudness judgment, however, since the 6 or 9 dB drop in intensity was obvious and the listener had to choose which part to focus on. All listeners chose the final segment, but it was clear that these tokens had two loudness values. This was never true for the speech stimuli, where listeners consistently matched the vowel level and the word provided a single loudness experience. Much more work is necessary to define and measure loudness as a function of time for complex nonspeech sounds.

Regardless of the overall similarity between speech and nonspeech loudness, however, the finding that words with increased C/V ratios are not louder has implications for research that may influence digital hearing aid design. It seems worthwhile to explore the intelligibility of words with high positive C/V ratios presented at levels near a hearing-impaired listener's loudness discomfort level (LDL). That is, there may be some impaired individuals who would show higher intelligibility for speech processed in this manner without experiencing any increase in loudness discomfort. It may be of value to note that processing to produce positive C/V ratios is only possible (if possible at all) in a digital hearing aid. Analog devices show no promise for detecting consonant-vowel boundaries, and simple analog processing such as amplitude compression can produce, at best, a zero C/V ratio.

A complete investigation of the effects of positive C/V ratios on the loudness and intelligibility of high-level speech should involve research with sentences and continuous discourse. The results of the present study suggest that such experiments may be worthwhile.

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