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A Critical Review of Acoustic Analyses of Aphasic and/or Apraxic Speech

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The study of speech production is, intuitively, a critical aspect of the study of apraxia of speech (AOS). However, in the study of aphasia, typically characterized as a language disorder, the need to study speech production may not be as apparent. McNeil and Kent (1990) argued that because of "the high probability of motor deficits coexisting with, or actually accounting for, many of the deficits labeled as aphasic, it is reasonable that the speech motor control abilities of aphasic populations should have received experimental attention" (p. 352). Furthermore, McNeil and associates reviewed acoustic, perceptual, and physiologic data from investigations of aphasic and/or apraxic subjects and concluded that the traditional classifications of AOS and aphasia syndromes should be reconsidered in light of observations of movement-level disturbances in AOS, Broca's aphasia, conduction aphasia, and Wernicke's aphasia. Other authors have also questioned the use of current descriptors in the study of acquired neurogenic speech disorders (Square-Storer and Apeldoorn, 1991; Rosenbek and McNeil, 1991; Weismer and Liss, 1991).

The study of neurogenic speech disorders has frequently taken the form of acoustic analysis of spoken productions (Baum, Blumstein, Naeser, and Palumbo, 1990; Kent and Rosenbek, 1983; Strand and McNeil, 1987; Ziegler and Hoole, 1989). Investigators have examined numerous aspects of aphasic and/or apraxic speech, such as voice onset time (VOT), vowel durations (Baum et al., 1990; Collins, Rosenbek, and Wertz, 1983), formant trajectories (Kent and McNeil, 1987; McNeil, Liss, Tseng, and Kent, 1990), fricative durations (Harmes, Daniloff, Hoffman, Lewis, Kramer, and Absher, 1984), and total word durations (McNeil et al., 1990; Square-Storer and Apeldoorn, 1991). If the existing literature in this area is to play a role in determining appropriate descriptors and classifications of neurogenic

speech–language disorders, the scientific merit of this database deserves assessment. Additionally, a critical review of this literature may assist in the design of future research efforts directed toward the study of speech production deficits in AOS and aphasia.

The primary purpose of this report was to conduct a summarization and critical review of investigations of acoustic analyses of aphasic and/or apraxic speech in order to evaluate the scientific adequacy of such reports. Because of the relatively wide array of analyses conducted across a variety of aphasic and/or apraxic speakers, a primary goal of this report was to provide a means for comparing and evaluating the reviewed investigations. Given the currently evolving state of AOS and aphasia description and classification, no attempt was made to separate these disorders in this review.

The following journals were searched from 1974 to the present for pertinent articles: *Brain and Language, Clinical Aphasiology, Journal of the Acoustical Society of America, Journal of Phonetics, Journal of Speech and Hearing Research,* and *Neuropsychologia.* Investigations cited in studies from these sources and those found in related texts were also considered for inclusion in this review.

Reports were initially selected for review if the following minimal criteria were met: (a) investigators specified that subjects were aphasic and/or apraxic; (b) at least one type of acoustic analysis was performed and; (c) quantitative or qualitative data from the acoustic analysis were presented. The following additional inclusion criteria were then applied to the 41 investigations meeting the initial selection criteria: (a) subject diagnoses were provided and were based on results of standardized test administration or on consensus diagnoses made by qualified personnel (e.g., certified speech–language pathologists and/or neurologists); (b) type of acoustic analysis was specified; and (c) stimuli were described in sufficient detail to allow for replication.

A total of 34 investigations were included in the review. In order to facilitate summarizations and comparisons of investigations, studies were grouped by type of acoustic analysis and summary tables were prepared. Each study was evaluated in terms of adequacy of subject description, reliability of aphasia diagnostic judgments, provision of AOS diagnostic criteria, description of stimuli and elicitation procedures, description of analyses and instrumentation, reliability of dependent measures, and provision of perceptual and physiologic data. In addition, a brief summary of findings was provided for each investigation.

SUBJECT DESCRIPTION

Overall, it was encouraging to find that of the original 41 investigations, only four were excluded on the basis of subject description criteria and

those were investigations conducted prior to 1983. All of the remaining investigations reported use of at least one standardized test, with the Boston Diagnostic Aphasia Examination being used most frequently. Twenty percent of the studies utilized consensus diagnosis in addition to objective measures. Most of the investigations could have been strengthened by the inclusion of actual test and subtest scores. Additionally, investigators rarely provided information regarding recruitment and selection or exclusion of subjects. Most reports did not address how potentially confounding factors such as dysarthria and dementia were treated.

Fifty-three percent of the aphasic subjects were described as being nonfluent, anterior, or Broca's. Another one-fourth of the subjects were described as fluent, posterior, Wernicke's, or anomic. The remaining subjects were described as having conduction aphasia or were not classified by type. Approximately 45% of the studies included information about the presence or extent of apraxia of speech in their aphasic subjects. Only a few subjects (9%) were described as being apraxic with minimal or no aphasia.

The number of aphasic and/or apraxic subjects in the investigations ranged from 1 to 16, with the mean number being 7. Most of the studies included some nonaphasic control subjects, with numbers ranging from 0 to 11. The majority of aphasic and control subjects were male. It appeared that the same subjects were sometimes used in more than one investigation (Blumstein, Cooper, Goodglass, Statlender, and Gottlieb, 1980; Shinn and Blumstein, 1980; Katz, 1987; Katz, 1988; McNeil et al., 1990; Weismer and Liss, 1991). Therefore, the total number of subjects studied by acoustic methods could not be accurately determined.

METHODOLOGICAL DESCRIPTIONS

Reports were excluded from this review if investigators did not report the exact stimuli used to elicit speech samples. Six of the original 41 reports were excluded for this reason. Of the 34 reviewed studies, 97% included specific information about elicitation procedures (e.g., repetition, oral reading) and 85% detailed the number of times stimuli were presented. A weakness in this area, noted across the majority of the studies, was a lack of specification of constraints placed on production attempts. Investigators did not usually indicate how often subjects were allowed to attempt productions or how behaviors such as false starts, groping, and repetitions were treated.

All of the investigations provided descriptions of the acoustic analyses performed. Eighty-two percent of the reports included information regarding instrumentation used in the analyses. However, with a few

exceptions (Baum et al., 1990; Duffy and Gawle, 1984), most studies did not provide detailed operational definitions for the measured dimensions. Another major problem noted with most of the investigations was a failure to detail the handling of erroneous productions. It was often unclear whether incorrect productions were included in the analyses, or if only accurate or on-target productions were utilized. As indicated by Weismer and Liss (1991), important information can be sacrificed if only error-free productions are analyzed.

PERCEPTUAL AND PHYSIOLOGICAL DATA

Related to the issue of thoroughly describing the speech samples submitted to analysis is the issue of perceptual data. We included the category of perceptual data in the review because we felt that when perceptual data accompanied acoustic data, a clearer picture of the subjects' speech emerged. Additionally, clinical applicability may be more evident when perceptual information is included in this type of research. Studies listed *yes* under this category provided either perceptual descriptions of the subjects' speech or findings of speech perception experiments based upon the subjects' speech samples. Approximately half of the investigations included some perceptual information with most being descriptive in nature.

The category of physiological data was included for reasons similar to the inclusion of the perceptual data category. However, physiological data were collected along with acoustic data in only 5% of the studies and these data were not included in the same reports.

RELIABILITY

A lack of reliability measurement was a ubiquitous problem across this group of studies. Only 18% of the investigations included any report of reliability of measurement of the variables under study. This is particularly disconcerting in light of the lack of provisions of operational definitions. One cannot assume that measurements were made accurately and reliably because acoustic measures may be more objective than traditional perceptual measures. Inter- and intrajudge reliability measurements should be reported for at least 25% of the speech samples (prior to segmentation) to assure the reader that obtained values were reliable.

SUMMARY OF STUDIES GROUPED BY FOCUS

Voice Onset Time

Table 1 includes all of the investigations in which VOT were analyzed. Some investigations were focused only on VOT (Shewan, Leeper, and Booth, 1984), whereas others included VOT as just one part of the investigation (Baum et al., 1990; Collins, Rosenbek, and Wertz, 1983).

Oral reading and/or repetition was used to elicit CV or CVC words in most of the VOT studies. In general, nonfluent aphasic subjects were found to have overlapping VOT values for voiced and voiceless cognates, with only a few exceptions (Hoit-Dalgaard, Morray, and Kopp, 1983). Fluent aphasic subjects tended to have VOT values and patterns similar to normals.

Prosodic Dimensions

Studies in which aspects of prosody were analyzed through acoustic measures are included in Table 2. These investigations included measures of F_0 contour, relative F_0, relative and total durations, and intensity. Table 2 excludes those studies in which durational measures were not specifically directed toward a study of prosody. Although there is a limited database from which to summarize, most of the subjects displayed abnormalities in prosodic dimensions, as evidenced by reduced intensity variation, relatively flat F_0 contour, limited F_0 range, and lengthened transitions. Basic aspects of prosody, such as F_0 fall for terminal words in a sentence, may be maintained for many subjects. All but one of the investigations were based on measures performed on speech samples obtained through oral reading and/or repetition. That is, these aspects of prosody were measured in highly controlled conditions, that did not allow for the opportunity to measure more natural prosody.

Vowel Studies

Table 3 summarizes the investigations in which vowels were analyzed acoustically. Vowels were studied in a variety of contexts: in isolation, in CVC words, in CVC minimal contrast word pairs, in polysyllabic words, and in words in phrases. Measures of vowel duration were performed more often than any of the other vowel measures.

Table 1. Studies of Voice Onset Time (VOT) in Aphasic and/or Apraxic Speech

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Acoustic Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Baum, Blumstein, Naeser, & Palumbo (1990)	4B 4NF (ant. & post.) 5F (4W & 1 Con)	no	VOT fricative duration vowel duration	acoustic wave form	daC real words taC 5 real words Final C varied; oral reading (repetition if S could not read)	no (only for data exclusion)	no	Note: 1 B excluded from VOT analysis Post Ss showed clear separation of VOT values for cognates; Ant/Post Ss and 2 of 3 Bs showed sig. overlapping of VOTs; 1 B showed clear separation of VOTs for t/d
Blumstein, Cooper, Zurif, & Caramazza (1977) 2-part experiment a. perceptual b. production	a. 8Ant(6B;2Mixed); 8Post(4W;2Con;2A); 4normal;4RHD b. 4B;1Mixed;3A;2W 1Con 3normal;1RHD	no	VOT	spectrographic	Tom, tot, top, dock, Don, dock (and 6 filler words with bilabial and velar stops–not analyzed); oral reading (somewhat unclear)	not of Ss' speech but of their perception	no	Normals' VOT ranges showed no overlap (t: −10 to +27msec; d:+55 to +76msec); 3 Anomic & 1 RHD performed normally; 1 W had paraphasic errors but VOTs were separated; 1 B VOTs overlapped in the +25 to +40 range where few normal values found; remaining Ss not described
Blumstein, Cooper, Goodglass, Statlender, & Gottlieb (1980)	4 B 4Con 5W 4 normal 1 D	not of Ss' speech but of their perception	VOT	spectrographic	30 monosyllabic real words: 5 words of each sound (p,t,k,b,d,g) w/in the phrase "this_____"; oral reading; repetition if necessary	no	no	Sig. main effect for group only (diff. between W and B groups). Noted more "phonetic" errors for Bs than Ws.
Collins, Rosenbek, & Wertz (1983)	10 male; 1 female w/ PICA overall: 7.78–14.29; 10 male normal; 1 female normal, age and education matched	yes, rating scale	VOT vowel duration stem word duration total word duration	spectrographic	3 sets of words of increasing length (e.g., "please-pleasing-pleasingly"); repetition	no	no	Analysis done only on "please" set: no statistically sig. differences between groups

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Acoustic Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Hoit-Dalgaard, Morray, & Kopp (1983)	6 male AOS, only 1 of the 6 agrammatic; PICA: 18th–88th percentile	yes, severity rating	VOT	spectrographic	bees-peas; repetition plus visual stimulus	not of Ss' speech but of their perception	yes, 10% of VOTs	VOTs had no overlap for 4 of 5 Ss, but voiceless values tended to fall in range (< 35 msec) considered to be voiced in most normals; several Ss had restricted range of VOTs. No relationship between Ss' perception of VOT and their productions. Severity of AOS did not predict performance.
Itoh, Sasanuma, Tatsumi, Murakami, Fukusako, & Suzuki (1982) Experiment 1	4 male AOS (2 w/ & 2 w/out aphasia); 6 male F (4 W & 2Con) 4 normal young male; 5 normal "aged" male	no	VOT	spectrographic	de, te, ge, ke (Japanese syllables); oral reading of randomized list	no	no	Qualitative analysis: AOS Ss showed considerable overlap in VOT between voiced and voiceless cognates; F Ss' date similar to normals with negligible overlap
Itoh, Sasanuma, Tatsumi, Murakami, Fukusako, & Suzuki (1982) Experiment 2	4 male AOS (2 w/ & 2 w/out aphasia); 2 young male	no	VOT over time	spectrographic	de, te, ge, ke (Japanese syllables); oral reading of randomized list 4–38 months after first elicitation	no	no	Patterns changed (toward normal) for 2 of 4 AOS subjects (these Ss were younger, of more recent onset, and had more aphasia than other 2 AOS subjects)
Kent & McNeil (1987)	3 male AOS, no detectable aphasia; 2 male Con; 3 male normal, same age range	yes	VOT segment duration intersegment duration total duration formant trajectories	spectrographic	"poppy" from "Buy, Bobby a poppy," repetitions of taped stimuli	yes, but not presented	no	Apr S had longer and more variable VOT values; Con 1's values like Apr; Con 2 had short VOTs

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Table 1. Studies of Voice Onset Time (VOT) in Aphasic and/or Apraxic Speech (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Acoustic Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Kent & Rosenbek (1983)	7 male w/"some" aphasia, not agrammatic; 7 normal males, slightly younger age range	yes	VOT	spectrographic	peep, tote, koke, gag; repetition	yes	no	Apr Ss' values similar to normals
Shewan, Leeper, & Booth (1984)	5 male B 4 female B; 4 male Con 1 female Con 6 female normal 3 male normal, comparable in age	no	VOT	spectrographic	70 CVC words beginning with p/b, k/g, t/d (about 12 tokens per sound); repetition, as well as showing Ss the printed word	no	no	No statistically sig. differences for mean VOTs among groups (B, Con, normals); VOTs for older normals differed from previous data from young normals
Ziegler & von Cramon (1985)	1 male B 3 male normal 1 D male, all younger	yes	VOT formant trajectories	unclear–probably waveform	gəti: tə; gəty: tə; gətu: tə (German); repetition w/in the phrase "I have heard ____"	no	no	VOTs varied but tended towards increased values

Note: Apr=Apraxic; AOS= Apraxia of speech; A=Anomic; B=Broca's; C=Consonant; F=Fluent; RHD=Right hemisphere-damaged; S=Subject; VOT=Voice onset time; V=Vowel; W=Wernicke's; X=mean

Table 2. Studies of Prosodic Dimensions

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Colson, Luschei, & Jordan (1986)	2 male AOS w/mild "expressive" aphasia 1 female AOS w/mild "expressive" aphasia 2 male normal 1 female normal, age and sex matched	no	F_0 of each syllable voice intensity (peak amplitude) syllable duration	waveform	30 phrases consisting of nonsense disyllables (e.g. /pəkʌ/); repetition of taped stimuli	yes, but not reported	no	For accurate productions, no sig. difference in F_0 btwn normal and Apr groups. Both groups tended to change F_0 relative to stress. For accurate productions, Apr Ss produced a greater contrast in F_0 compared to normals. Significantly less change in F_0 by Apr Ss for productions produced with inaccurate stress. No sig. difference btwn the groups' intensity for accurate productions. Both groups produced unstressed syllables with greater intensity than stressed syllables. Apr Ss produced similar intensity changes for syllables produced with inaccurate stress placement.
Cooper, Soares, Nicol, Michelow, & Goloskie (1984)	2B 3W 4 age-matched normal	no	F_0 of 1st & last stressed word of single clause sentences; F_0 of stressed syllables of 2-clause sentences F_0 vowel duration: final word, entire sentence, pauses, clauses	unclear	12 and 18 sentences of increasing length; "Al wants peaches . . . Al wants to buy some peaches . . . Al wants to buy a 3 lb. box of peaches"; oral reading	no	no	Both groups produced abnormally high F_0s at both measured locations; relatively flat F_0 contour for Bs. Both Bs and Ws, like normals, produced higher F_0 at first measured location.

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Table 2. Studies of Prosodic Dimensions (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Danly & Shapiro (1982)	5 male B 5 age-matched normals (sex not indicated)	no	F_0 word duration	waveform F_0 plot	oral reading of sentence pairs	no	no	Bs had statistically sig. F_0 fall for final words; significant declination of F_0 from 1st to 2nd word
Kent & Rosenbek (1983)	7 male w/AOS and "some coexisting aphasia" 7 normal male, slightly younger age range	yes	intensity envelope F_0 contour VOT vowel duration formants F1-F2 comparisons	visipitch spectrographic	sentence repetition	yes	no	Intensity: Apr Ss gave greatest intensity to same syllables as normals, showed less intensity variation, had smaller mean intensity reduction; F_0: Apr Ss preserved terminal fall, F_0 values similar to normals
Colson, Luschei, & Jordan (1986)	8 male w/"motor" aphasia ("few phonemic substitutions") 11 normal male, similar age range	no	range of fundamental frequency of 5th harmonic vowel duration sentence duration	spectrographic	Construisons notre maison; repetition of stimuli (live voice for aphasic and taped stimuli for normals)	no	no	Statistically sig. restriction in range of fundamental frequency for aphasic; no significant correlation between length of production and range
Square-Storer & Apeldoorn (1991)	1 male AOS, no aphasia 2 female AOS, no aphasia 1 normal male	yes	prosodic patterns: relative syllable length, relative syllable intensity Duration: polysyllabic words and syllabic nuclei, monosyllabic words	waveform spectrographic mean absolute voltage	5 polysyllabic words; oral reading, repetition	samples transcribed	yes, for acoustic measures (w/in 10% of the original)	Overall findings question the appropriateness of dysprosody as a criteria for AOS; 2 Ss showed excessive lengthening of unstressed syllables
Weismer & Liss (1991)	4 male AOS, no aphasia 4 male normal	yes	F_0 amplitude contours, temporal patterning	spectrographic (used stackplots)	stressed words in phrases elicited in contrastive stress drill	yes, included transcriptions	no	Gave limited examples from Ss

Table 3. Studies of Vowels

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Baum, Blumstein, Naeser, & Palumbo (1990)	4 B 4NF (ant. & post.) 5F (4W & 1Con)	no	vowel duration VOT fricative duration	waveform perception	CVCs; oral reading; repetition if necessary	no	no	Overall V. durations by Ant aphasic group were longer than those of Ant/Post & Post aphasic group.
Code & Ball (1982)	1 female B 1 normal female	provided descriptors	vowel duration preceding voiced/voiceless fricatives; fricative duration	spectrographic	17 minimal pairs contrasting voiced and voiceless fricatives. Manner of elicitation not specified	no	no	V durations were maintained within normal limits.
Collins, Rosenbek, & Wertz (1983)	10 male; 1 female w/PICA overall: 7.78–14.29; 10 normal male; 1 normal female, age and education matched	yes, rating scale	vowel duration VOT stem word duration total word duration	spectrographic	3 sets of words of increasing length (e.g., "please-pleasing-pleasingly"); repetition	no	no	Increased duration for Apr for 2 sets but not for the third set ('zip'); ratios of V to word durations very similar for groups.
Cooper, Soares, Nicol, Michelow, & Goloskie (1984)	2B 3W 4 age-matched normal	no	F_0vowel; F_0 of 1st and last stressed word of single clause sentences; F_0 of stressed syllables of 2-clause sentences; Duration: final word, entire sentence, pauses, clauses	unclear	2 sets of sentences (12 & 18); oral reading	no	no	Left hemisphere Ss more deviant than right hemisphere Ss. Both groups produced abnormally high Fs at both sentence locations.

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Table 3. Studies of Vowels (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Duffy & Gawle (1984)	2 male F 2 male, predominately NF 1 male AOS, predominately F 1 male AOS, predominately NF 3 female AOS, predominately NF 2 male normal 3 female normal	yes	vowel duration preceding final stop	oscillographic and spectrographic	beet - bead;pick - pig; cop - cob; repetition of taped stimuli	yes, description of speech	yes, agreement w/in 10 msec	Apr & aphasic varied V duration ratios comparable to normals; both Apr & aphasic were not normal in V duration or precision of control. Apr tended to have shorter than normal V durations & > variability.
Gandour & Dardarananda (1984)	1 male RHD 2 female B 1 male transcortical motor 1 male Con 1 female W 1 female D 2 normal male; 3 normal female	no	vowel length for phonemic contrast	spectrographic	3 minimal pairs vowel length phonemic in Thai; w/in the phrase" this is ____", oral reading; repetition if necessary	no	no	Normals had clear separation of phonemic variants of /a/; Ant aphasics had only occasional overlap of short and long V lengths; Post aphasics had no overlap; no statistically sig. differences in ratios of ranges of the Vs.
Kent & McNeil (1987)	3 male AOS, no detectable aphasia 2 male Con 3 normal male, same age range	yes	formant trajectories VOT Duration: segment, total, intersegment	spectrographic	"building" from "Buy a big building", repetition of taped stimuli	not reported	no	Apr 2, Apr 3, Con 1, & Con 2 more variable; had different placement on frequency axis & different temporal pattern; Apr1 similar to normals.

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Kent & Rosenbek (1983)	7 male w/"some" aphasia, not agrammatic 7 male normal, slightly younger age range	yes	1.vowel duration 2.formants 3.F1-F2 VOT intensity envelope F_0 contour total duration segment duration	spectrographic	1.selected words 2."please" in sentence 3./i,u,æ,o/ Repetition (some oral reading)	yes	no	1.V length increased as utterance length increased 2.Slower rate of F2 increase & longer transitions 3.Plotted against normal isovowel lines–overall Ss had adequate range but some individual extreme deviations.
McNeil, Liss, Taeng, & Kent (1990)	3 male AOS, minimal or no aphasia 2 male Con 3 normal male, same age range	yes	formant trajectories total duration segment duration	spectrographic	"aw" from "dog" "in" from "sixteen", repitition from taped stimuli; 3 rate conditions: control, slow, fast	yes	yes, portion of total measures recreated, resegmented & are measured by a 2nd investigator	Only data from one Apr S used: had same general pattern of slopes–greater in control and fast conditions than slow.
Ryalls (1981)	11 male "motor" aphasic 11 normal male	not stated	F_0, F1, F2 vowel duration word duration sentence duration	spectrographic	machination iturpala construisons notre maison Manner or elicitation not described	no	yes	Results for F_0 not stated; sig. differences between groups for F1; trend toward sig. variability of F2 for /a/ of "machination" and /ɛ/ of "maison"; durations of /a/, /i/, & /ɔ/ sig. longer for aphasic groups. Trend towards significance for /ɛ/ and /ɔ/.

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Table 3. Studies of Vowels (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Ryalls (1982)	8 male "motor" aphasic ("few phonemic substitutions") 11 normal male, similar mean age	no	vowel duration range of F_0 of 5th harmonic sentence duration	spectrographic	Construisons notre maison; repetition of stimuli (live voice for aphasic and taped stimuli for normals)	no	no	Statistically sig. increase in length of vowels for aphasic group.
Ryalls (1984) Experiment 1	5 male B 6 male W 1 male Con 7 male normal	7 male normal	F_0	autocorrelation & waveform	9 CVC (hVd) words; oral reading; repetition if necessary	for data exclusion	no	Sig. difference in mean F_0 between Ant aphasic group & normals but not between Ant & Post aphasic groups; both aphasic groups had significantly greater standard deviations in F_0s than normal; inherent differences in F_0 among Vs maintained for all groups. Sig. difference in standard deviations of period-to-period perturbations between post aphasic and normal groups.
Ryalls (1984) Experiment 2	5 Ant 5 Post (These 10 were chosen from the subjects above)	5 male normal chosen from the subjects above	period to period variation pitch to pitch variation	autocorrelation & waveform	subset from above words; oral reading; repetition if necessary	for data exclusion	no	See results above.

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Ryalls (1986)	5 male B 6 male W 1 male Con 7 normal (sex not indicated)	no	vowel duration F_0, F1, F2	spectrographic	head, hod, hud, hid, had, hood, heed, hawed, who'd; oral reading; repetition if necessary	for data exclusion	no	Variability in V durations significantly greater than normal in Ant Ss; however, durations not statistically significantly longer; Post patients had largest durations; no sig. differences in formant means even with a normalization procedure designed to compensate for vocal tract length.
Sussman, Marquardt, Hutchinson, & MacNeilage (1986)	8 male B 5 female B	provided verbal apraxia scores	spectral peaks of F1 and F2	FFT	vowels: /i,a/; repetition, but somewhat unclear	no	no	Compared bite block(bb) formant values to non-bite block values; most Ss had higher F1 & lower F2 values in bb condition, indicating undershoot of tongue elevation & fronting for /i/; no clear patterns for /a/; sig. negative correlations between formant difference values and BDAE scores & verbal apraxia scores; also related CT data to bb values.

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Table 3. Studies of Vowels (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Ziegler & von Cramon (1985)	1 male B 3 male normal 1 male D	yes	formant trajectories VOT	LPC	gəti: tə; gəty: tə; gətu: tə (German); repetition w/in the phrase "have heard ___"	no	no	F2 range exceeded normals' range
Ziegler & Hoole (1989)	1 male B 1 male W 1 male normal 1 male D	no	vowel duration, F1-F2 trajectories and quality perception	LPC	2 German words varying only in 1st vowel; repetition	yes	no	Plotted V by duration vs. F1-F2 differences: Normals & D had no overlap, B had some overlap in F1-F2 dimension, W overlapped on both dimensions; listeners identified words in 3 conditions; misclassifications low for Normals & D, W had most misclassification across range, B misclassifications occurred on Vs overlapping in the F1-F2 dimensions.

Note: Ant=Anterior; Apr=Apraxic; B=Broca's; Con=Conduction; C=Consonant; D=Dysarthric; FFT=Fast Fourier transform; LPC=Linear predictive coding; V=Vowel

In these investigations, nonfluent aphasic subjects frequently had longer and more variable vowel durations than normals, although this was not always observed (Ryalls, 1986). In cases in which vowel durations carried phonemic significance, aphasic patients, in general, maintained that significance.

The findings of these investigations reveal that both fluent and nonfluent aphasic speakers may exhibit abnormally high F_0s, but may maintain inherent F_0 differences among vowels. Additionally, subjects may display deviations and increased variability in formant trajectories and values.

Durational Studies (excluding vowels)

In addition to durational measures of vowels and prosody, many other durational measures have been performed and are presented in Table 4. These include investigations of the duration of fricatives, syllables, monosyllabic words, polysyllabic words, clauses, pauses, interword intervals, and sentences. The variety of durational measures combined with the variety of subjects and stimuli used in these investigations precludes further summarization in this report.

Other Studies

Studies of coarticulation are included in Table 5. The coarticulatory effects of vowels have been measured by a few investigators and findings are far from conclusive. It appears that coarticulatory effects have been seen for both fluent and nonfluent aphasic subjects, but that coarticulatory effects may be delayed for some nonfluent subjects.

Two studies of consonant spectra, without a special focus on coarticulation, are also included in Table 5.

CONCLUSION

These 34 investigations have allowed us to see aspects of apraxic and/or aphasic speech that are unavailable through more traditional, perceptual means. Whether the findings from these investigations have clarified or clouded our understanding of apraxia and/or aphasia is debatable. Only VOT studies provide an extensive and fairly conclusive database. While the data from vowel and durational studies are substantial, replications of findings are not as evident as with VOT. Studies of prosody and coarticulation have just begun to give new insights. Much more research is needed in the areas of vowel and duration, prosody and coarticulation.

Generality of findings from this group of investigations is limited due to the relatively small number of subjects studied and problems with subject description. Future research efforts should include direct and systematic replications of previous research in all areas. Although acoustic analyses remain labor intensive, recent technological advances should allow for the study of many more subjects than was previously possible, i.e., computerization has significantly shortened the time needed to perform many analyses.

While greater subject numbers are needed to establish the reliability and generality of previous findings, more in-depth study of individual subjects is also warranted. Concentrating on individual subjects would allow the study of individual variability, which has usually been overlooked in acoustic studies (Weismer and Liss, 1991). As pointed out by Square-Storer and Apeldoorn (1991), this area of research would be strengthened by investigators taking a holistic approach to the study of their subjects' speech. Along these lines, future research efforts should include more precise and extensive reports of speech and language testing.

In addition to reporting results of psychometric testing, investigators should provide phonetic transcriptions of the speech samples under analysis. If speech samples are too extensive to provide such data, investigators should provide transcription reliability data. As noted previously, investigators should specify whether erroneous and/or error-free productions were analyzed and how multiple attempts at targets were treated.

Because there is limited information about which acoustic parameters are important in the perception of specific sounds, researchers should be encouraged to include experiments of speech perception in their study of aphasic and apraxic speech. This is particularly important if these acoustic measures are to have clinical relevance. If clinicians are to use this information for diagnostic or treatment purposes, they need to know the relative importance of these various acoustic measurements in terms of speech perception.

Perhaps the most problematic aspects of this literature review were the lack of reliability reports and the absence of operational definitions. Researchers need to operationally define all behaviors/parameters measured and report inter- and intrajudge reliability for all acoustic and perceptual measurements. Given the variability in performance often observed with apraxic and/or aphasic populations (Weismer and Liss, 1991), future research efforts should also be directed toward examining reliability of these various acoustic measurements over time.

Overall, findings from this group of 34 investigations should be interpreted cautiously. Certainly, this research has provided important groundwork for better understanding of aphasic and/or apraxic speech disorders. However, these results are far from conclusive and would best be utilized as a springboard for more rigorous research efforts.

Table 4. Durational Analyses (Excluding Vowels)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Baum, Blumstein, Naeser, & Palumbo (1990)	4B 4NF (ant. & post.) 5F (4W & 1 Con)	no	fricative duration vowel duration VOT	waveform	CV syllables containing 6 fricatives preceding each of 5 V; oral reading; repetition if necessary	no	no	Absolute durations: variability across Ss, with less variability seen for normals, however, similar results across groups with longer durations for /s/ & /ʃ/ than for /f/ & /θ/ (except for one NF); aphasic Ss also had relatively normal CV ratios; no aphasic S maintained normal durational difference between voiced & voiceless fricatives
Code & Ball (1982)	1 female B 1 normal female	provided descriptors	fricative duration vowel duration preceding voiced/voiceless fricatives	spectrographic	17 minimal pairs contrasting voiced and voiceless fricatives Manner of elicitation not indicated	provided descriptors	no	The B's S produced durations for voiced and voiceless fricatives that were longer than normal; no voicing occurred during voiced fricatives
Collins, Rosenbek, & Wertz (1983)	10 male; 1 female w/PICA overall: 7.78–14.29; 11 age, sex and education matched normal	yes, rating scale	duration: stem word, total word VOT vowel duration	spectrographic	3 sets of words of increasing length (e.g., "please-pleasing-pleasingly"); repetition	yes, rating scale	no	Word duration differences statistically sig. for "please" set ratios of V to word durations similar between groups

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Table 4. Durational Analyses (Excluding Vowels) (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Colson, Luschei, & Jordan (1986)	2 male AOS w/mild "expressive" aphasia 1 female AOS w/ mild "expressive" aphasia 2 male normal 1 female normal, age and sex matched	no	syllable duration	waveform perception	30 phrases consisting of nonsense disyllables (e.g./pekA/); repetition of taped stimuli	yes, but not reported	no	No sig. difference btwn normal and Apr groups' average relative syllable duration for accurate productions. Individually, some Apr Ss produced less durational contrasts, equal stress, smaller or greater durational changes than normals.
Cooper, Soares, Nicol, Michelow, & Goloskie (1984)	3B 3W 4 age-matched normal	no	duration: final word, entire sentence, pauses, clauses	oscillographic	12 sentences and 18 sentences: "Al wants peaches...Al wants to buy some peaches...Al wants to buy a 3 lb. box of peaches", oral reading	no	no	Present numerical values for all groups in all sentence lengths, but do not present results of any statistical comparisons; utterance lengths appear longer for B & W, but not RHD patients
Danly & Shapiro (1982)	5 male B 5 age-matched normal (sex not indicated)	no	word duration	waveform	oral reading of words in different positions of sentences	no	no	Statistically sig. lengthening of initial word, rather than final word like normals; but...not for medial to final words

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
DiSimoni & Darley (1977)	1 female AOS, minimal or no aphasia	yes	duration of /p/	oscillographic	ipi; ipi saw ipi; ipi saw ipi with ipi; repetition of taped stimuli	no	no	Decrease in /p/ duration from 1 to 3 syllables (not statistically sig.); increase in duration from 3 to 5 syllables (statistically significant); /p/ durations faster than normals
Harmes, Daniloff, Hoffman, Lewis, Kramer, & Abaher (1984)	2 male B 2 female B 4 age and sex matched normal	no	fricative duration relative duration	spectrographic	30/z/ & /z/ words; 1 to 3 syllables; repetition	none	no	Absolute fricative durations not statistically sig. in all contexts between groups; relative durations for group "strongly similar across all conditions" (e.g., initial vs. final)
Kent & McNeil (1987)	3 male AOS, no detectable aphasia 2 male Con 3 male normal, same age range	yes	Duration: segment, total, intersegment VOT formant trajectories	spectrographic	"buy Bobby a poppy" "build a big building"; repetition of taped stimuli	NA	no	Apr: had smaller % of utterance contributed by segmer durations compared to normals; intersegment durations 2-5 times length of nor mals during control rate; during fast rate, were withi normal limits; intersegment variability greater for Apr than normal & Con

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Table 4. Durational Analyses (Excluding Vowels) (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Kent & Rosenbek (1983)	7 male w/ "some" aphasia, not agrammatic 7 male normal, slightly younger age range	yes	total duration segment duration VOT	spectrographic	sentences & multisyllabic words selected words; imitation	none	no	Total duration sentences: all Apr values > normal by at least 2 sd; multisyllabic words: most durations longer than normals, but were highly variable–lengthening tended to be seen as artic. prolongation & syllable segregation; segment durations: stops & affricates in monosyllables same as normals, /s/ & /aetʃ/ longer; almost all consonants in multisyllabic longe
McNeil, Liss, Taeng, & Kent (1990)	3 male AOS, minimal or no aphasia 2 male Con 3 normal male, same age range	not stated	total duration segment duration formant trajectories	spectrographic	six, sixteen, stop fast, Bob hit the big dog; repetition of taped stimuli	yes	yes, portion of total measures recreated, and resegmented and are measured by a 2nd investigator	Total duration: increased for Apr Ss for fast & control conditions but not for slow condition
Ryalls (1982)	8 male w/"motor" aphasia ("few phonemic substitutions") 11 male normal, similar mean age	no	sentence duration range of F_0 of 5th harmonic vowel duration	spectrographic	Construisons notre maison; repetition of stimuli (live voice for aphasic & taped stimuli for normals)	no	no	Aphasics had significantly increased length of sentences

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Square-Storer & Apeldoorn (1991)	1 male AOS, no aphasia 1 male normal	yes	duration: polysyllabic words & syllabic nuclei, monosyllabic words prosodic patterns: relative syllable length, relative syllable intensity	waveform spectrographic mean absolute voltage	5 polysyllabic words, 4 monosyllabic words (dice, dime, leash, lid); reading, naming, repetition	samples transcribed	yes, acoustic measures (w/in 10% of original)	2 Ss' productions were longer than the normals -: Ss were not; Ss all differed in amounts of variability with S having little variability like the normal
Strand & McNeil (1987)	4 male; 1 female w/PICA overall: 13.6–14.6 and RTT:> 13.1	yes	IWI	spectrographic	word strings and sentences; repetition of taped stimuli	no	no	IWIs consistently longer for Apr Ss v. normal S for both of stimuli. Normal Ss consistently reduced IWI1 and IWI2 for sentences v. word strings. As a group, Apr Ss reduced IWI 1 for sentences v. word strings. Apr group also tender reduce IWI 2 for sentences v. word strings. However, individual S variability noted. Greater intra- and intersubject variability for the Apr Ss.

Note: Apr=Apraxic; B=Broca's; Con=Conduction; IWI=Interword interval; NF=Nonfluent; RHD=Right hemisphere damaged; S=Subject; V=Vowel

Table 5. Coarticulation and Other Studies

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Harmes, Daniloff, Hoffman, Lewis, Kramer, & Absher (1984)	2 male B 2 female B 4 age and sex matched normal	no	fricative spectral measures fricative duration relative duration	LPC	30 /s/ & /z/ words: 1 to 3 syllables; repetition	yes, more detailed than most; narrow phonetic transcription	no	Statistically sig. differences for all spectral measures across groups; aphasic /s/ spectra had more peaks than normals (as a group–1 had fewer); aphasic group had lower spectral cutoff frequencies (except 1); normals had higher central frequencies
Katz (1987)	5 male B (2 with D) 5 male Post (4W, 1 apraxic)	no	coarticulation spectral peaks of /s,t,k/	LPC	see - Sue tea - two key - coo stea - stew ski - skoo; oral reading; repetition if necessary	yes	no	sV & tV: no difference among groups; Ant aphasics had lower /ki/ values than other two groups; all groups showed "robust"/ki -ku/ coarticulation; 1 Ant had > than normal shift for s-blends; 1 Ant had < normal shift for s-blends; Perceptual study: 10 naive listeners identified V from consonant segment at levels significantly above chance for all groups, although Ant aphasic Vs were identified at lower levels.

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Katz (1988)		no	coarticulation spectral analysis	waveform LPC	Same stimuli and manner of elicitation as Katz (1987)	yes	no	sV, tV, & kV had sig. coartic. shift for all 3 groups in low frequency peaks; normals & Post patients had sig. coartic. for stV & skV; 1 B had < normal, 1B had > normal, & 1 B had normal shift for s-blends.
McNeil, Hashi, & Southwood (1994)	2 male AOS, minimal or no aphasia 3 male Con 1 male normal	yes	coarticulation	gating-perceptual study	/s/, /st/, /b/ + /I/ words /s/, /st/, /b/ + /i/ words Manner of elicitation not described	yes	no	Coarticulatory effects delayed for both apraxics and 1 Con aphasic; 1 Con demonstrated normal artic.
Shinn & Blumstein (1980)		no	spectral measures of consonants	LPC	Same as Blumstein et al. (1980); monosyllables starting with /b,d,g,p,t,k/	yes	no	Fit spectra to normal templates; B within normal ranges for acceptance of velar consonants & rejection of labials & velars; B greatly lower on acceptance of alveolars; when using only perceptually "correct" utterances, the fits were closer to normal–with alveolars still lower.

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Table 5. Coarticulation and Other Studies (continued)

Authors (Date)	*Subjects*	*Criteria for Apraxia of Speech*	*Measures Conducted*	*Analysis Type*	*Stimuli/ Manner of Elicitation*	*Perceptual Data*	*Reliability for Dependent Measures*	*Results*
Tuller & Story (1987)	3 male F 2 female F 4 male NF 1 female NF 5 normal, same age range	yes	coarticulation: center frequency bandwidths and amplitudes; spectral peaks for fricatives	LPC	2 word sequences containing combinations of /i/ and /u/ e.g., pea soup, new seat; oral reading with repetition	not provided	no	Anticipatory V effects (mean difference in F2 values): Controls had statistically sig. effects of 2nd V seen from midpoint of frication noise; F Ss results same as controls; NF, Ss–only 1 S showed significantly different F2 values as early as controls but when measured later in frication noise (after Katz, 1987), 2 additional Ss showed anticipatory effects.
Ziegler & von Cramon (1985)	1 male B, slight agrammatism in spontaneous speech 3 male normal 1 male D, all younger	yes	coarticulation VOT formant trajectories	gating-perceptual study	gəti: tə; gəty: tə; gətu: tə (German); repetition w/in phrase "I have heard___"	yes	no	For normals, G2 (time of /t/ burst release) was critical in listeners' perception of V; same for aphasic for /u/, but delayed until G3 for /i/ and G4 or G5 for /y/
Ziegler & von Cramon (1986)	1 male B, slight agrammatism in spontaneous speech 3 male normal 1 male D, all younger	yes	coarticulation: resonance	V: LPC Stops: reflection coefficients	Probably same stimuli as Ziegler & von Cramon (1985) Manner of elicitation not described	yes	no	Sig. coarticulatory effects for V seen at all measurement times for normals as evidenced by high rates of correct V classifications by discriminant functions; low rates of classification for aphasic (40–60%), indicating less coarticulation

Note: Ant=Anterior, B=Broca's; Con=Conduction; F=Fluent; G=Gate; LPC=Linear predictive coding; NF=Nonfluent; Post=Posterior, V=vowel; W=Wernicke's

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