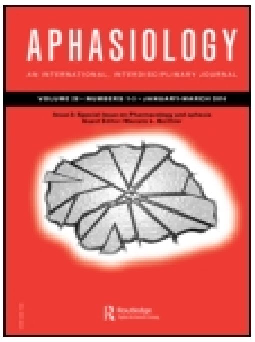

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An acoustic measure of lexical stress differentiates aphasia and aphasia plus apraxia of speech after stroke

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Background: Apraxia of Speech (AOS) is partly characterised by impaired production of prosody in words and sentences. Identification of dysprosody is based on perceptual judgements of clinicians, with limited literature on potential quantitative objective measures.
Aims: This study investigated whether an acoustic measure quantifying degree of lexical stress contrastiveness in three syllable words, produced in isolation and in a carrier sentence, differentiated individuals with AOS with/without aphasia (AOS), aphasia only (APH), and healthy controls (CTL).
Methods & Procedures: Eight individuals with aphasia, nine with AOS plus aphasia and 8 age-matched control participants named pictures of strong–weak and weak–strong polysyllabic words in isolation and in a declarative carrier sentence. Pairwise Variability Indices (PVI) were used to measure the normalised relative vowel duration and peak intensity over the first two syllables of the polysyllabic words.
Outcomes & Results: Individuals with aphasia performed similarly to control participants in all conditions. AOS participants demonstrated significantly lower PVI_vowel duration values for words with weak–strong stress produced in the sentence condition only, compared to controls and individuals with aphasia. This was primarily due to disproportionately long vowels in the word-initial weak syllable for AOS participants. There was no difference among groups on PVI_intensity.
Conclusions: The finding of reduced lexical stress contrastiveness for weak–strong words in sentences for individuals with mild to moderate–severe AOS is consistent with the perceptual diagnostic feature of equal stress in AOS. Findings provide support for use of the objective PVI_vowel duration measure to help differentiate individuals with AOS (with/without aphasia), from those with aphasia only. Future research is warranted to explore the utility of this acoustic measure, and others, for reliable diagnosis of AOS.

Keywords: Lexical stress; Prosody; Apraxia of speech; Acoustic analysis; Aphasia; Pairwise variability index.

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Apraxia of speech (AOS) is a "phonetic-motoric disorder" of speech production that disrupts retrieval and/or implementation of movement plans for speech sounds, despite normal muscle tone and strength (McNeil, Robin, & Schmidt, 2009). Those affected have slow speech with distorted consonants and vowels and are perceived to produce words and phrases with syllable segregation and equal stress across adjacent syllables. These signs of AOS have been attributed to poorly planned timing and positioning of articulators (e.g., McNeil et al., 2009). The present study focused on production of lexical stress in polysyllabic words, which is important for intelligibility and naturalness of speech (Arciuli & Cupples, 2004, 2006; Arciuli & Slowiaczek, 2007; Klopfenstein, 2009; Paul et al., 2005; Peppé 2009; Slowiaczek, 1990; Wingfield, Lombardi, & Sokol, 1984). The primary aim was to investigate whether lexical stress is produced differently in individuals with AOS plus aphasia compared to those with aphasia only and age-matched healthy control participants. Findings have potential to guide design of more sensitive assessment and intervention protocols.

LEXICAL STRESS

In stress-timed languages such as English, lexical stress follows a roughly alternating pattern of stressed and unstressed syllables, also referred to as strong (S) and weak (W) stress, respectively (Fletcher, 2010). In English, the strong–weak (SW) stress pattern is predominant for polysyllabic words, with nouns typically associated with a SW stress pattern and verbs with a weak–strong (WS) pattern (e.g., Arciuli & Slowiaczek, 2007; Sereno, 1986). Strong syllables tend to have longer duration, greater vocal intensity and higher fundamental frequency than weak syllables. It has been suggested that, for English, duration is the most salient cue for stress pattern (Klatt, 1976) and fundamental frequency (f_0) the least reliable indicator, at least in isolated word production (Arciuli & Slowiaczek, 2007; Ballard, Djaja, Arciuli, James, & van Doorn, 2012; Choi, Hasegawa-Johnson, & Cole, 2005). Consistent with this, in this study we focused on vowel duration and peak intensity of the vowel.

Production of lexical stress with left hemisphere damage

Production of linguistically meaningful stress in individuals with left hemisphere brain damage has received considerable attention. These studies have focused on variations in lexical stress assignment associated with lexical and non-lexical decoding routes in reading aloud (Cappa, Nespor, Ielasi, & Miozzo, 1997; Galante, Tralli, Zuffi, & Avanzi, 2000; Laganaro, Vacheresse, & Frauenfelder, 2002; Miceli & Caramazza, 1993), picture naming and spontaneous speech (Cappa et al., 1997; Laganaro et al., 2002), and duration and pitch variations in syllables variously positioned in words, phrases or sentences (e.g., Danly & Shapiro, 1982; Emmorey, 1987; Ouellette & Baum, 1994). Some studies have reported that individuals with aphasia can show errors of stress assignment, with WS words produced with the more frequent SW pattern. Notably, this error profile has been reported in languages other than English, particularly Italian. Stress assignment errors are infrequently observed in English speakers with aphasia (Howard & Howard, 1999) and individuals with AOS are described as having reduced stress contrastiveness rather than errors in stress assignment (e.g., McNeil et al., 2009).

Investigations of lexical stress in tasks examining markers of word boundaries (e.g., blackboard vs black board) and grammatical category (e.g., REcord vs reCORD) (e.g., Ouellette & Baum, 1994; Walker, Joseph, & Goodman, 2009) have reported reduced stress contrastiveness in individuals with left versus right hemisphere damage, particularly for control of syllable or vowel duration. This has contributed to a general conclusion that the left hemisphere is critical for specification and control of timing in word and sentence production (Alcock, Wade, Anslow, & Passingham, 2000; Niemi, 1998; Sidtis & Van Lancker-Sidtis, 2003; Zatorre & Belin, 2001). Further, it has been argued that different timing errors with left hemisphere lesions are associated with frontal damage compared with posterior damage, although Seddoh (2008) reported that timing errors are more common in individuals with non-fluent aphasia (i.e., frontal lesions; Seddoh, 2008). Similarly, Baum and Boyczuk (1999) suggested that timing errors can appear at all levels in non-fluent aphasia, from monosyllabic words through to sentences, but typically only in longer multisyllabic words or sentences in fluent aphasias. One argument is that non-fluent speakers are showing the effects of multiple impairments, with phonetic errors at the level of the phoneme or syllable and disruptions due to syntactic planning difficulties over longer units (Balan & Gandour, 1999; Gandour, Dechongkit, Ponglorpisit, & Khunadorn, 1994; Seddoh, 2004, 2008). It is reasonable to hypothesise that these two types of timing errors are associated with different behavioural profiles, AOS and agrammatic aphasia, respectively.

AOS is typically associated with frontal lesions (Duffy, 2005; Robin, Jacks, & Ramage, 2008). Presence or absence of AOS in individuals with non-fluent aphasia has not been well described in the literature on stress production to date. While some studies have stated that individuals with motor speech disorder were excluded from their samples, few have provided the necessary detail about how presence or absence of a motor speech disorder was determined. Others have not mentioned the possibility of AOS affecting performance. Furthermore, the bias towards examining the linguistic specification and representation of stress has resulted in few studies considering articulatory influences on the production of an assigned stress pattern. One exception was Howard and Howard (1999), who elegantly laid out the predictions from various theories of language production as to the types of errors related to lexical stress that might occur in aphasia. These encompassed errors of stress assignment, transposition of vowels or syllables and omission of unstressed syllables. Contrary to studies in other languages, such as Italian, they observed that none of their English-speaking patients with aphasia made stress assignment errors but they tended to omit or duplicate syllables. One potential explanation that they offered for this pattern was that initial weak syllables may be more difficult to articulate, a combination of the tendency for initial weak syllables to be very brief and to show greater coarticulation that stressed syllables. One would expect this to affect individuals with AOS more so than those without AOS, due the articulatory impairment in AOS. However, as noted by Howard and Howard, their four participants with concomitant AOS were not uniform in their error profile for frequency and location of syllable omission errors within words and did not make more errors than the participants without AOS. Acoustic measures of speech may provide further insight into these influences on speech production in individuals with aphasia with/without AOS.

Difficult producing polysyllabic words with weak onset syllables has been reported numerous times across a range of populations. Children achieve adult-like production of stress contrastiveness in SW nouns by 3 years of age, while production of the less typical WS stress pattern in nouns is not yet adult-like at 7 years of age (Ballard et al., 2012). Snow (2007) suggested that it is physiologically easier to transit from a strong syllable to a weak syllable than vice versa. This is linked to increased activation of the respiratory muscles required to produce a longer duration and louder segment, and greater activation of laryngeal muscles to increase loudness and pitch (Ladefoged, 1993). Given the motoric complexity of controlling and producing rapid changes in stress within words, it is not surprising that both children and adults with motor speech disorders are often perceived to have impaired lexical stress production (Ballard, Robin, McCabe, & McDonald, 2010; Duffy, 2005; Hosom, Shriberg, & Green, 2004; Shriberg et al., 2003). Inability to adequately vary the parameters of vowel duration, intensity and/or f_0 to produce varied stress patterns may lead to reduced intelligibility (Klopfenstein, 2009) and monotonous, robotic sounding speech. These speech difficulties can result in communication failure and social withdrawal (Duffy, 2005).

Production of lexical stress in apraxia of speech

Dysprosody has been identified as a primary feature of acquired AOS, manifested by equal and excess stress and syllable segregation (Duffy, 2005; Kent & Rosenbek, 1983; McNeil et al., 2009; Odell & Shriberg, 2001). The perception of equal stress has been related to weak syllables being stressed to a similar degree as strong syllables. Syllable segregation has been described as insertion of brief pauses between syllables, potentially though not necessarily leading to the perception that syllables are produced as "separate units of similar duration, and uniform intensity and frequency contours in words and phrases" (Odell & Shriberg, 2001). The overlap in these two descriptions, or constructs, is clear. Auditory perceptual methods (e.g., Peppé & McCann, 2003; Shriberg, 1993) are most often used to detect and classify lexical stress patterns (van Santen, Prud'hommeaux, & Black, 2009). While perceptual judgments are considered a golden standard in speech pathology practice (Duffy, 2005), they are susceptible to bias and drift (Kent, 1996) and potential conflation of behaviours or concepts, as noted above.

The relative ease in measuring the duration and intensity cues to lexical stress is a promising starting point for developing instrumental acoustic measures of apraxic speech that might allow more reliable diagnosis and differentiation from aphasia. Several acoustic measures have been useful in measuring prosodic variation across different languages (e.g., Courson et al., 2013; Low, Grabe, & Nolan, 2000), across different age groups (e.g., Ballard et al., 2012), across language disordered populations (e.g., Balan & Gandour, 1999; Walker et al., 2009) and across speech disordered populations (e.g., Ballard et al., 2010; Hosom et al., 2004; Patel & Campellone, 2009). Comparisons of absolute acoustic values such as segment, syllable or word duration, and peak f_0 and peak vocal intensity have been used in several studies (e.g., Casper, Raphael, Harris, & Geibel, 2007; Patel, 2004; Strand & McNeil, 1996). However, Ladefoged (1993) suggested that relative values of pitch, duration and intensity within the same utterance should be more informative than absolute values for examining stress patterns.

Ratio measures to capture prosodic contrasts were used by Balan and Gandour (1999) and Shriberg et al. (2003), while Walker et al. (2009) used acoustic measures normalised across all utterances produced by each speaker. The "lexical stress ratio" (LSR) (Shriberg et al., 2003) was developed to study lexical stress production in the childhood form of AOS and is a single composite measure of duration, intensity and f_0. Research has shown that speakers may use any one or combination of these three variables to mark stress and a composite measure such as the LSR should capture stress pattern regardless of these variations (van Santen et al., 2009). While such a measure is useful, an argument can be made for examining each variable separately because control over them may be differentially affected, or informative, across motor speech disorders.

The relative measure of lexical stress employed in the current study is the Pairwise Variability Index (PVI), which was originally designed to study the rhythmic properties of various languages (Low et al., 2000). The PVI is a measure of relative vowel duration (or intensity or f_0) across adjacent syllables in a word or sentence that is normalised to allow comparison across different speech rates and habitual intensity and f_0 levels of individuals within a sample. The PVI measure involves calculating the difference in duration (or intensity or f_0) for two adjacent syllables and dividing the difference by an average of the two values. High PVI values indicate greater contrastiveness while values close to zero indicate equal stress.

Based on Ziegler's psycholinguistic framework (Ziegler, 2002), the characteristics of AOS should not vary with the type of speech task being elicited, but rather the complexity of the task. For example, Strand and McNeil (1996) reported that individuals with AOS produced significantly longer vowel durations in sentences than in isolated words. Hence, there is support for investigating lexical stress produced in three-syllable words in both isolation and in a more complex sentence condition, using the PVI as a normalised relative measure of vowel duration. Previous studies have tended to use two-syllable multisyllabic words, which are susceptible to final syllable lengthening (Collins, Rosenbek, & Wertz, 1983; Strand & McNeil, 1996). Here, three-syllables words were used to examine lexical stress production over the initial two syllables, without the final syllable lengthening confound. Furthermore, given the paucity of information on receptive prosody skills of adults with left-hemisphere stroke and potential influences of receptive deficits on production, we assessed aspects of receptive prosody related to our experimental expressive prosody tasks (Peppé & McCann, 2003).

Development of an instrumental measure of lexical stress that has high sensitivity and specificity for differentiating AOS from commonly confused conditions, such as aphasia with phonological paraphasias, could lead to increased diagnostic accuracy and improved quantification of baseline function or change over time. Such outcomes may also stimulate development of more specific interventions (Ballard & Robin, 2002; Ballard et al., 2010).

The purpose of the current study was to determine whether an acoustic measure of lexical stress is associated with expert judgment of AOS presence and severity in cases with or without concomitant aphasia, a task commonly facing clinicians. The primary hypotheses were as follows:

(1) Individuals with AOS (with/without aphasia) will demonstrate reduced contrastiveness for vowel duration and intensity across the first two syllables of three-syllable words, in both isolated word and sentence conditions, compared to healthy controls and individuals with aphasia only.
(2) Any reduction in stress contrastivity for the AOS participants, relative to aphasia and control participants, will be more pronounced in a sentence context than in isolated word production.

METHOD

All study procedures were approved by the University of Sydney's Human Research Ethics Committee and the Sydney South West Area Health Service. All participants provided informed consent.

Participants

Participants were identified from a larger study of speech and language disorders after stroke. Inclusion criteria for the larger study were broad, and included adults who were fluent speakers of English premorbidly but now had any type of expressive speech or language disorder subsequent to a single left hemisphere stroke. Participants also reported no previous history of speech, language or neurological impairment or substance abuse, and no uncorrected visual or hearing impairment. They were recruited via advertisement to stroke support networks and speech-language pathology clinics. Exclusion criteria for the present study were dysarthria more severe than AOS or aphasia, aphasia quotient (AQ) on the Western Aphasia Battery–Revised (WAB-R; Kertesz, 2006) ≤ 40/100, and a WAB-R word repetition score ≤ 2/10, indicating inability to repeat three-syllable words.

Of 52 consecutive cases, 17 met inclusion criteria and agreed to participate. All underwent diagnostic testing with a speech-language pathologist to define the nature of their impairments (see Table 1). These included (a) the language subtests of the WAB-R to determine presence and severity of aphasia, (b) a motor speech examination (Duffy, 2005), the Apraxia Battery for Adults-2 (ABA-2; Dabul, 2000), and the Story Retell Procedure (McNeil et al., 2007) to generate speech samples for expert diagnosis of AOS and dysarthria, (c) the Auditory Discrimination subtest of the Psycholinguistic Assessments of Language Processing in Aphasia (Kay, Lesser, & Coltheart, 1992) to assess auditory discrimination of words, (d) the receptive subtests of the Profiling Elements of Prosody in Speech- Communication (PEPS-C; Peppé & McCann, 2003) to document any difficulties in perceiving prosodic variations in words and sentences, (e) the Raven's Coloured Progressive Matrices, included in the WAB-R, as an index of nonverbal cognitive function and (f) a pure-tone hearing screening. All participants passed hearing screening in at least one ear at 40 dB HL for 1,000 and 2,000 Hz (Ventry & Weinstein, 1983).

Judgments on presence and severity of AOS, dysarthria and phonological paraphasias were made by expert raters, the currently accepted golden standard method (Duffy, 2005). The scores from the ABA-2 were not used in diagnosis due to their conflation of phonological paraphasic and AOS signs and the resultant high false positive rates for identifying AOS. A 20 minute video was compiled showing each participant's performance on a range of tasks from the Motor Speech Examination and the ABA-2 as well as the Story Retell Procedure, including non-speech orofacial movements, alternating and sequential motion rates, multisyllabic word production, sentence production, story retelling and a reading of the Grandfather Passage. Presence and severity of AOS, dysarthria and phonological paraphasias were rated according to published guidelines (Duffy, 2005; McNeil et al., 2009) by two to three speech-language pathologists, each with over 30 years of clinical experience. A Likert-type 7-point scale was used (from 0 being absent, 1 being minimal/questionable, to 6 being severe). All samples were judged by two raters and, when ratings diverged by more than one point, the video was judged by a third rater; the majority diagnosis regarding presence/absence was used for group assignment and severity was

TABLE 1
Demographic details and test scores for participants with apraxia of speech with/without aphasia and participants with aphasia only

	Apraxia of speech (AOS)			*Aphasia (APH)*		
Demographics & test scores	*Mean*	*SD*	*Range*	*Mean*	*SD*	*Range*
Age (Years)	59.3	6.1	49–68	66.4	9.0	49–77
Sex	7 Male, 2 Female			6 Male, 2 Female		
Education	14.4	3.0	11–19	13.1	2.5	10–17
Months post-onset	30.6	17.3	6–58	38.0	51.8	10–161
Western aphasia battery—revised[1]						
Aphasia quotient (/100)	68.3	14.0	41.6–88.1	72.8	17.6	50.0–97.3
Fluency (/10)	5.1	2.6	2–9	6.5	2.5	4–10
Information content (/10)	6.9	1.5	3–8	8.4	1.8	5–10
Auditory comprehension (/10)	8.3	1.4	6.3–9.9	8.0	1.5	6.1–9.8
Repetition (/10)	6.6	2.0	2.6–8.9	6.2	2.4	2.6–10
Naming (/10)	7.2	1.4	5.4–9.6	7.3	1.9	5.0–9.2
Reading (/60)	48.6	8.8	37–60	46.0	16.6	24–60
Ravens coloured progressive matrices						
Score (/36)	30.9	2.8	28–36	27.4	4.6	19–34
Psycholinguistic assessments of language processing in aphasia[2]						
Auditory discrimination (/72)	64.4	5.8	53–70	65.1	5.6	56–72
Motor speech examination[3]						
AOS severity	2.9 mild–mod	1.0	2–5	0.1 absent	0.2	0–1
Dysarthria severity	0.1 absent	0.2	0–1	0.2 absent	0.4	0–1
Phonological paraphasia severity	2.1 mild	1.5	0–4	2.3 mild	1.0	0–4
Perceived dysprosody	4 Present, 3 Absent, 2 Questionable			1 Present, 6 Absent, 1 Questionable		
Profiling elements of prosody in speech—communication[4]						
Focus	74.0	15.6	50–95	65.6	19.2	45–100
Intonation	69.4	20.3	31–95	72.3	18.2	38–94
Prosody	81.8	13.9	56–95	75.0	11.0	63–88
Turn-end	58.7	24.6	28–90	67.6	17.5	44–94

Age, education, months post-onset and Aphasia Quotient did not differ significantly for AOS and APH groups. *M* = Male; *F* = Female; NA = Not assessed; [1]Kertesz (2006); [2]Kay et al. (1992); [3]Duffy (2005): AOS, dysarthria, and phonological paraphasia severity rating scale with 0 = absent, 1 = minimal, 2 = mild, 3 = mild-moderate, 4 = moderate, 5 = moderate-severe, 6 = severe (scores are averaged over two raters, see text for details), dysprosody was defined as one/more of the three features—increased duration of segments, increased duration of intersegment transitions/pauses, and equal stress, Questionable = disagreement between raters; [4]Peppé and McCann (2003).

recorded as the average of those two scores. Four disagreements of greater than 1 point were noted for AOS and/or phonological paraphasia ratings and in three of these the disagreement involved the decision on presence/absence; in all three cases, the third rater judged AOS to be present and the case was assigned to the AOS group. Five of nine cases assigned to the AOS group and seven of eight assigned to the APH group were judged as producing phonological paraphasias. The original two judges showed 100% agreement on absence of AOS in the APH participants and agreed in 16/17 cases on ratings of dysarthria. To further describe participant's speech, the expert raters indicated presence or absence for seven features commonly observed, though not necessarily unique to AOS; only ratings on presence of dysprosody are reported in Table 1, for comparison with acoustic measurement of lexical stress.

Participants were of Caucasian (N = 15) and Asian (N = 2, 1 per group) ethnicity, aged between 49 and 77 years. Nine participants were judged to have AOS plus aphasia (AOS; 7 male and 2 female; mean age = 59.3 years, SD = 6.1) and eight with aphasia but no AOS (APH; 6 male and 2 female; mean age = 66.4, SD = 9.0). Note that APH5 achieved an AQ of 97.3, in the normal range on the WAB-R (Kertesz, 2006), but he demonstrated clear residual language formulation and word-finding difficulties that have precluded his return to work and so he was retained in the APH group. There was no significant difference in the WAB-R AQ scores for the AOS and APH groups (p > .05). Mean scores across the four receptive subtests of the PEPS-C considered related to the experimental task were not different between the AOS and APH groups (AOS mean scores ranged from 59% to 82% correct; APH mean scores ranged from 66% to 75% correct) (see Table 1).

In addition to participants in the AOS and APH groups, eight healthy adults (mean age = 66.6, SD = 9.4; 3 males and 5 females) were recruited as controls (CTL) (see Table 2). All reported no known neurological disease or uncorrected hearing or vision impairment, except CTL4 who reported acquired corrected bilateral hearing impairment. There was no significant difference in age across the AOS, APH and CTL groups. Due to the limited adult norms for the PEPS-C test, six of the eight control participants were tested. For the four subtests of the PEPS-C administered, both AOS and APH groups performed significantly lower than the CTL group (p < .05) with CTL mean scores ranging from 89% to 97% correct.

TABLE 2
Control participants' demographic details and scores for the test Profiling Elements of Prosody in Speech-Communication (PEPS-C)

	Control (CTL)								
Measures	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Mean (SD)*
Age (years)	77	74	63	64	76	70	50	59	66.6 (9.4)
Sex	F	F	M	M	M	F	F	F	
Profiling Elements of Prosody in Speech-Communication[1]									
Focus	100	100	100	100	38	100	na	na	89.6 (25.5)
Intonation	94	100	100	88	100	100	na	na	96.9 (5.2)
Prosody	94	94	94	94	88	94	na	na	92.8 (2.6)
Turn-end	94	94	100	100	50	94	na	na	88.6 (19.1)

AOS, APH and CTL participant groups did not differ significantly by age; na = not assessed; [1]Peppé and McCann (2003).

Stimuli

Ten common three-syllable nouns were selected; five with a strong–weak stress pattern (SW: dinosaur, motorbike, cardigan, barbeque, bicycle) and five with weak–strong pattern (WS: potato, tomato, banana, pyjamas, detergent). Regarding the third syllable, for some words in each set this syllable receives secondary stress in Australian English and for some it is unstressed (i.e., weak). For consistency in reference throughout and to highlight that the analysis included only the first two syllables, we label the words beginning with a strong–weak pattern as SW and words beginning with a weak–strong pattern as WS. All words had a CVCV structure for the first two syllables and contained between six and eight phonemes with no consonant clusters. Frequency for the SW words ranged from 0 to 7 (median = 1) and for the WS words 3 to 26 (median = 5) (see Table 3; Davis, 2005). These words were selected to allow unambiguous identification of onset and offset for the first and second vowels, for later acoustic analysis. Note that postvocalic "r" is silent in Australian English and the vowel of the weak syllable is reduced, typically to a schwa. Ten university students named the picture stimuli with 100% accuracy to ensure they elicited the correct target word.

Two Microsoft PowerPoint presentations were developed to elicit the words in each speaking condition: isolated word production and production in a declarative carrier sentence (i.e., "Here is the [word]"). Two additional conditions probing contrastive stress and interrogative intonation were elicited at the same time but are not reported here. Each presentation included one slide per stimulus word, with the picture and the target word or carrier sentence written beneath.

Tasks and procedures

Participants were seated in front of a laptop computer in a quiet room. Both speaking conditions were preceded by five practice items, which were pictures not included in the stimulus set. The participants were instructed to name the picture or say the sentence and were encouraged to produce the sentence without hesitation before the target word. The lexical task was presented first; order of the target words or utterances within each of the speaking conditions was randomised.

If the participant was unable to produce an independent response to a picture, a semantic cue (e.g., "We use it to wash dishes") was provided, then a phonemic cue if necessary. Thus, three unsuccessful attempts were permitted before presenting a pre-recorded model by a female Australian-English speaker for imitation. The first complete production of each target word in each condition was used for analysis.

Apparatus

An Interacoustics (Assens, Denmark) AS608 Screening Audiometer and Peltor (St Paul, MN, USA) H7A headband headset were used for pure tone hearing screening in a sound treated booth. The experimental protocol and the PEPS-C subtests were presented to participants using Hewlett-Packard Pavilion g4 and Sony Vaio portable computers, respectively, with free-field auditory presentation in a quiet room. The participants' responses during each of the experimental tasks were recorded with a 48 kHz sampling rate and 16-bit resolution using a Marantz (Kanagawa, Japan) PMD661 solid-state recorder, with AudioTechnica (Tokyo, Japan) ATM75 cardioid headset microphone placed 5 cm from the mouth.

TABLE 3
Psycholinguistic measures (frequency and phonological structure) of each stimulus word

	Frequency						Phonological structure		
Stress pattern	*CELEX – T*	*CELEX – W*	*CELEX – S*	*Kucera frequency*	*BNC*	*SMH*	*Log 10*	*CV_p*	*Number of phonemes*
Strong–Weak									
Dinosaur	1.7	1.8	0.8	1	3.0	4.4	0.4	CVCVCV	6
Bicycle	17.9	18.7	8.5	6	8.8	6.1	1.3	CVCVCVC	7
Cardigan	2.3	2.4	1.5	0	3.1	1.6	0.5	CVCVCVC	7
Barbeque	0	0	0	0	0	0	0	CVCVCVV	7
Motorbike	2.7	2.7	3.1	7	5.0	6.1	0.6	CVCVCVC	7
Median	2.3	2.4	1.5	1	3.1	4.4	0.5		7
Weak–Strong									
Tomato	6.8	7.4	0.8	5	7.2	13.6	0.9	CVCVCV	6
Potato	11.5	12.3	1.5	15	7.8	10.7	1.1	CVCVCV	6
Banana	4.1	4.3	1.5	4	4.8	9.0	0.7	CVCVCV	6
Pyjamas	0	0	0	3	0	0	0	CVCVCVC	7
Detergent	5.1	5.5	0	26	2.7	1.0	0.8	CVCVCVCC	8
Median	5.1	5.5	0.8	5	4.8	9	0.8		6

CELEX database frequency of occurrence for both written and spoken corpora (T), written corpora only (W), and spoken corpora only (S) (Baayen, Piepenbrock, & van Rijn, 1995); Kucera frequency gives the frequency of occurrence in written language (Kucera & Francis, 1967); BNC = Frequency of occurrence in written modern British English (British National Corpus); SMH = Frequency of occurrence in written articles in the Sydney Morning Herald (Dennis, 1995); Log10 = logarithm of a word's frequency; CV_p = consonant-vowel structure; Insufficient data to report imageability or subjective familiarity (MRC Psycholinguistic database, Coltheart, 1981; Bird, Franklin, & Harold, 2001). Data extracted using the N-Watch program (Davis, 2005; http://www.pc.rhul.ac.uk/staff/c.davis/Utilities/).

Dependent measures

All acoustic measures were made by the first author, blinded to speech diagnosis at the time of measurement. The speech analysis software Praat (http://www.fon.hum.uva.nl/praat/) (Boersma & Weenink, 2010) was used to measure vowel duration (sec) (from onset to offset of clear formant structure of the vowel) and peak intensity (dB SPL) over the nucleus of the vowel for the first two syllables of each target word.

These measures were converted to Pairwise Variability Indices (PVI_vowel duration and PVI_intensity) using the formula below (Ballard et al., 2010; Low et al., 2000). This generates a PVI value for each production for each participant. Smaller values indicate less constrastivness, or more equal stress, across adjacent syllables.

$$\mathrm{PVI_x} = 100 * \mathrm{ABS}\big((\mathrm{X_{syll\ 1}} - \mathrm{X_{syll\ 2}})/((\mathrm{X_{syll\ 1}} + \mathrm{X_{syll\ 2}})/2)\big)$$

where x is the dependent variable of vowel duration or vowel peak intensity.

Although the PVI_vowel duration measure is normalised for speech rate, we acknowledge that individuals with AOS have slowed speech rate relative to controls and individuals with aphasia and that slowed speech rate can differentially affect strong and weak syllables (Ziegler, Hartmann, & Hoole, 1993). Therefore, we specifically tested for a relationship between speech rate and the PVI_vowel duration measures. The total duration of the first two syllables of each word for each participant was measured, from word onset to the onset of the audible portion of the third syllable (e.g., the onset of plosive burst for "b" in motorbike or frication noise for "s" in dinosaur). Only the first two syllables were included as this directly corresponds to the unit of speech measured for the PVI.

Inter-rater reliability

To calculate inter-rater reliability on the measures of vowel duration and intensity, a second rater measured 15% of the total sample of 500 words (i.e., 10 words × 2 conditions × 25 participants). Intra-class correlation coefficients were .88 for vowel duration and .99 for peak intensity.

STATISTICAL ANALYSIS

Prior to analysis, skewness and kurtosis for each variable were examined. These were statistically significant for vowel durations in initial strong vowels, initial weak vowels and medial weak vowels in both the isolated word and sentence conditions, as well as for the total duration measures. Thus, these data were log transformed prior to analysis. Original values are presented in figures for ease of interpretation.

For each PVI measure, a separate one-way ANOVA was conducted with a between subjects factor of group (AOS, APH, CTL). Tukey post-hoc tests were used to examine pairwise group differences. To explore significant effects for the PVI_vowel duration measure, separate ANOVAs were computed for vowel durations for each syllable type and position (i.e., strong vowel in the first syllable, weak vowel in second syllable, weak vowel in first syllable, and strong vowel in second syllable), with the between subjects factor of group and Tukey post-hoc tests.

To explore a potential influence of speech rate on PVI_vowel duration, we performed a sequence of analyses. First, a repeated measures ANOVA tested for group (AOS, APH, CTL) and condition (SW-word, SW-sentence, WS-word, WS-sentence) effects on total duration, with a Tukey post-hoc test for group and paired *t*-tests for planned pairwise post-hoc testing of condition (SW-word vs SW-sentence, WS-word vs WS-sentence, SW-word vs WS-word, SW-sentence vs WS-sentence; alpha level 0.0125 adjusting for multiple comparisons). Finally, correlations between total duration and PVI_vowel duration in the four conditions were computed using the Pearson coefficient.

RESULTS

Pairwise variability index measures

Isolated word condition. Only the group comparison of PVI_vowel duration on WS words reached significance (WS: $F(2,22) = 4.341$, $p = .026$, η2partial = .283; SW: $F(2,22) = .114$, $p > .05$) (see Figure 1). The η2partial value indicates that 28.3% of the between subjects variance on PVI for WS words is accounted for by the group variable. Tukey post-hoc tests revealed that the AOS group had a significantly smaller PVI_vowel duration on WS words compared to the APH group ($p = .037$), while the comparison between AOS and CTL participants approached significance ($p = .066$). The APH group performed similarly to the CTL group. The PVI_intensity measure was not significantly different for SW or WS words among the three groups (SW: $F(2,22) = 2.059$, $p > .05$; WS: $F(2,22) = .144$, $p > .05$).

Sentence condition. Similarly, only the group comparison of PVI_vowel duration on WS words reached significance (WS: $F(2,22) = 9.902$, η2partial = .474, $p = .001$; SW: $F(2,22) = 2.477$, $p > .05$) (see Figure 1). The η2partial value indicates that 47.4% of the between subjects variance on PVI for WS words is accounted for by the group variable. Tukey post-hoc tests revealed that the AOS group had significantly smaller

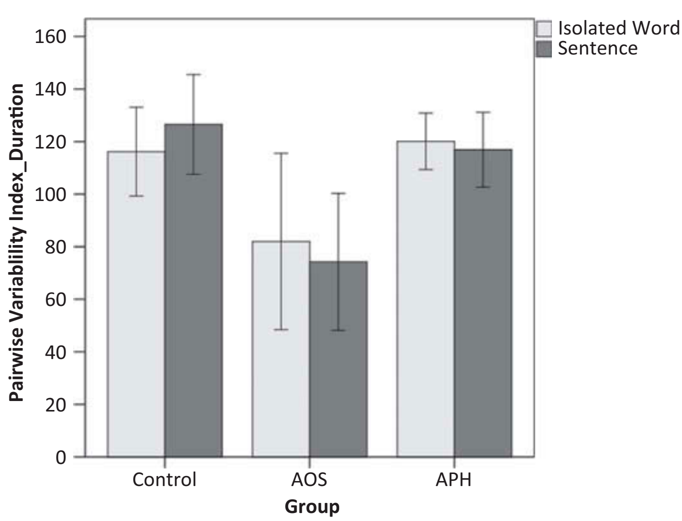

Figure 1. Pairwise Variability Index for vowel duration on weak–strong words (e.g., potato) in the isolated word (pale grey) and sentence (darker grey) conditions for control participants (Control) and individuals with aphasia plus apraxia of speech (AOS) or aphasia alone (APH). Bars represent averages for each group with 95% confidence intervals.

PVI_vowel duration on WS words compared to both the APH group (p = .007) and the CTL group (p = .001). Six of the 9 AOS participants had values below the range for the CTL and APH groups. The small range of AOS severity in this sample precluded a correlation analysis. Of the three AOS participants with relatively normal PVI values, two were judged by expert raters to have mild AOS while the other was judged to have moderate AOS. The APH group performed similarly to controls. The PVI_intensity measure was not significantly different for SW or WS words among the three groups (SW: $F(2,22) = 1.279$, $p > .05$; WS: $F(2,22) = .662$, $p > .05$).

Vowel duration measures

Isolated word condition. Vowel duration for weak and strong syllables in first and second syllable position did not differentiate the groups (initial syllable strong: $F(2,22) = 2.226$, $p > .05$; initial weak: $F(2,22) = 3.106$, $p = .065$; second syllable strong: $F(2,22) = .519$, $p > .05$; second weak: $F(2,22) = 2.257$, $p > .05$) (see Figure 2).

Sentence condition. Vowel duration within weak syllables in both first and second syllable position showed a significant group effect ($F(2,22) = 14.114$, $p < .001$, $\eta^2_{\text{partial}} = .562$ and $F(2,22) = 5.289$, $p = .013$, $\eta^2_{\text{partial}} = .325$, respectively) (see Figure 3). The η^2_{partial} values indicate that 56.2% and 32.5% of the between subjects variance for weak vowel duration in first and second syllable position, respectively, is accounted for by the group variable. The AOS group had significantly longer weak vowel durations in both initial and medial syllables, compared to both CTL ($p < .001$

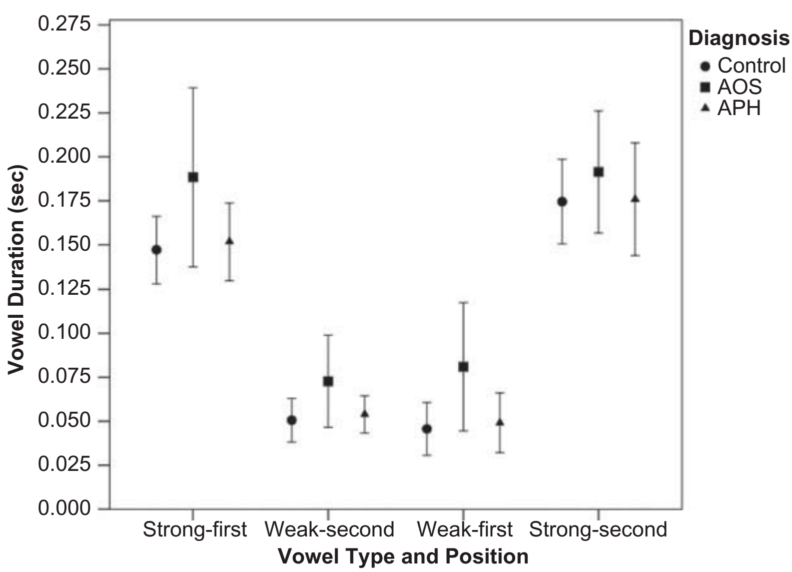

Figure 2. Vowel duration for strong and weak vowels in first and second syllable position for the isolated word condition for control participants (Control; circle symbol) and individuals with aphasia plus apraxia of speech (AOS; square symbol) or aphasia alone (APH; triangle symbol). The Strong-first and Weak-second values are derived from Strong–Weak words such as dinosaur, the Weak-first and Strong-second values from Weak–Strong words such as potato. Symbols represent averages for each group with 95% confidence intervals. Note that durations for initial strong vowels and initial and medial weak vowels were log transformed prior to analysis.

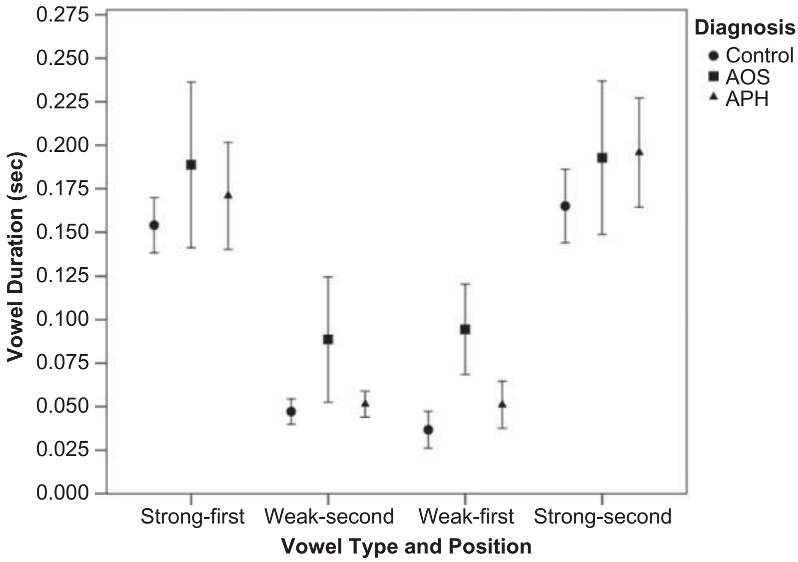

Figure 3. Vowel duration for strong and weak vowels in first and second syllable position for the sentence condition for control participants (Control; circle symbol) and individuals with aphasia plus apraxia of speech (AOS; square symbol) or aphasia alone (APH; triangle symbol). The Strong-first and Weak-second values are derived from Strong–Weak words such as dinosaur, the Weak-first and Strong-second values from Weak–Strong words such as potato. Symbols represent averages for each group with 95% confidence intervals. Note that durations for initial strong vowels and initial and medial weak vowels were log transformed prior to analysis.

and p = .020, respectively) and APH participants (p = .003 and p = .039, respectively), with the CTL and APH groups not significantly different. Strong syllable vowel duration was not influenced by group (initial syllable strong: $F(2,22) = 1.316$, $p > .05$; second syllable strong: $F(2,22) = 1.264$, $p > .05$).

Speech rate

Repeated measures ANOVA revealed significant effects of group and condition on speech rate ($F(2,22) = 8.196$, $p = .002$, $\eta^2_{partial} = .427$ and $F(1,22) = 10.509$, $p = .004$, $\eta^2_{partial} = .323$), but not for the interaction term ($F(2,22) = .007$, $p > .05$). The $\eta^2_{partial}$ values indicate that 42.7% of the between subjects variance in speech rate is accounted for by the group variable and 32.3% by the condition variable. Tukey post-hoc testing revealed that the AOS group had significantly longer total duration than the CTL group (mean difference 0.199 sec, SE = .053, p = .001). The APH group was intermediate and not significantly different from either the AOS or CTL group (mean difference from AOS 0.109 sec, SE = .053, $p > .05$; mean difference from CTL 0.090 sec, SE = .054, $p > .05$). Paired t-tests examining the condition effect revealed that two comparisons were significant. Total duration of SW tokens in the isolated word condition were significantly shorter than in the sentence condition (Mean = .426 sec, SEM = .028, and Mean = .469 sec, SEM = .033, respectively; $t(24) = -4.446$, $p < .001$). SW-word durations also tended to be shorter than total durations of WS tokens in the word condition, but did not survive Bonferroni correction (WS-word Mean = 0.450 sec, SEM = .025; $t(24) = -2.225$, $p = .036$).

For WS tokens in both isolated word and sentence conditions, longer total duration was associated with more equal stress captured by smaller magnitude PVI_vowel duration, although the correlation with WS words in sentences did not survive adjustment for multiple comparisons (r = .531, p = .006, and r = .437, p = .029, respectively). No other conditions reached significance (SW-word: r = –.058, SW-sentence: r = –.103; p > .05).

DISCUSSION

This study investigated the use of acoustic measures of relative vowel duration and vocal intensity to examine production of lexical stress in polysyllabic words. Based on published descriptions of the diagnostic features of AOS, it was hypothesised that individuals with AOS plus aphasia would show smaller PVI values, indicative of equal and excess stress, compared with individuals with aphasia alone or healthy control participants. Furthermore, we predicted that any differences between these groups would be more pronounced as the speaking condition increased in complexity from isolated words to simple carrier sentences.

Our hypotheses were largely supported with PVI values for vowel duration being significantly smaller in magnitude for weak–strong words for the AOS group compared to the group with aphasia alone or healthy controls, although peak intensity of vowels did not differentiate the groups. This difference in relative vowel durations across groups was stronger for the sentence condition than the isolated word condition. Consistent with this finding, the AOS group demonstrated significantly longer vowel durations for the vowels in the initial weak syllable position of words (e.g., potato), with vowel durations for strong syllables being similar to controls, although somewhat more variable as a group. Of interest, the AOS participants produced normal lexical stress contrastiveness for strong–weak words. These effects do not appear to be explained simply by AOS speakers having a generally slower speaking rate, as the measure of speech rate was significantly correlated with PVI_vowel duration measures for the weak–strong words only, not the strong–weak words. This supports disproportionate difficulty for individuals with AOS in producing polysyllabic words with weak onset syllables, but not weak medial syllables.

Previous studies have reported that healthy adults mark lexical stress by varying duration and vocal intensity across stressed and unstressed syllables (Arciuli & Slowiaczek, 2007; Ballard et al., 2012; Choi et al., 2005; Sluijter, van Heuven, & Pacilly, 1997). Here, the PVI measure of relative vowel durations and peak vowel intensity captured these stress patterns within words; on examination of signed PVI values prior to conversion to absolute values, all participants consistently produced all stimulus words with the appropriate stress pattern, supporting findings of Howard and Howard (1999). However, only the magnitude of the PVI values for vowel duration differed across groups. Relative vowel duration has been previously proposed as a sensitive measure of lexical stress (Klatt, 1976; Ladefoged, 1993) and as an important diagnostic feature of apraxic speech (Kent & Rosenbek, 1983; Shriberg et al., 2003; Strand & McNeil, 1996). However, the group with AOS did overlap with the other two groups on the measure of PVI_vowel duration for weak–strong words; of the nine individuals with AOS tested here, three fell in the range of the control and aphasia samples. While further study with a larger sample and a broader range of AOS severity is required, our data suggest that PVI_vowel duration alone may not be sufficiently sensitive to the presence of AOS in stroke to stand alone as a diagnostic marker. Murray, McCabe, and Ballard (2012) found that a combination of three to four perceptual measures best predicted expert diagnosis of the childhood form of AOS. However, Ballard et al. (2014) recently demonstrated that a composite index representing PVI_vowel duration for both SW and WS words in individuals with primary progressive non-fluent aphasia and/or AOS showed 88% agreement with expert judgment of presence of AOS in 17 cases.

Others have reported that AOS speakers tend to lengthen steady state segments (Kent & Rosenbek, 1983) and demonstrate longer vowel durations in multisyllabic words as compared to monosyllables (Strand & McNeil, 1996). Of those studies using acoustic measures to investigate prosodic contrasts in individuals with AOS or dysarthria, there has been the tendency to use disyllabic words (Courson et al., 2013; Patel & Campellone, 2009; Shriberg et al., 2003). The present study restricted stimuli to the analysis of the initial two syllables in three-syllable nouns, avoiding the confound of final syllable lengthening. In doing so, our data suggest that lengthening of segments is not uniform across all segments or syllables in a word. Specifically, vowels in weak syllables tend to be disproportionately lengthened compared to vowels in strong syllables, and this is particularly evident when the weak syllable initiates the word (also see Ballard et al., 2014). While speech-language pathologists may pay attention to the perceptual feature of equal lexical stress in diagnosing AOS, data reported here suggest that the main problem underlying this perception is the control of relative timing, not lexical stress per se.

It is noteworthy that the individuals with AOS in this sample had reduced lexical stress contrastiveness only for weak–strong words. Jusczyk, Cutler, and Redanz (1993) drew attention to the lower frequency of this stress pattern on nouns and suggested that, for children, protracted development may reflect lower exposure. The findings from perceptual studies with adults, indicating that lexical decisions for weak–strong words are slower than for strong–weak words, suggest this frequency effect persists through life. While it has been shown that syllables with lower frequency in the language tend to be shorter in duration (e.g., Cholin, Dell, & Levelt, 2011; Laganaro, 2008; Laganaro, Croisier, Bagou, & Assal, 2012), the weak syllables in our words were of high frequency and of similar frequency for strong–weak and weak–strong words. As such, it is unlikely that syllable frequency explains these findings.

It is perhaps more likely that individuals with AOS have difficulty with weak–strong words due to the motoric challenge of producing segments of very brief duration; these segments increase the rate of transitioning from the articulatory positions for the weak syllable into those for the strong syllable. Here, the older healthy adults tended to produce shorter vowel durations for initial weak syllables compared to medial weak syllables, particularly in the sentence condition. A similar finding was reported by Ballard et al. (2012) for young adults producing isolated three syllable words. Our participants with AOS, for the sentence condition in particular, demonstrated weak vowel durations almost twice the duration of healthy controls and participants with aphasia alone. This difficulty with transitioning rapidly from one syllable to the next is a hallmark feature of AOS.

The severity of AOS in this sample ranged from mild to moderate–severe. It is possible that a group of more severe patients would have shown a more pronounced reduction in stress contrastiveness and possibly across both weak–strong and strong–weak words. When restricting stimuli to three syllable words containing tense vowels in the strong syllable, the level of contrastiveness for healthy adults appears reasonably consistent with average PVI_vowel duration for weak–strong words ≥ 110 and for strong–weak words ≥ 80 (Ballard et al., 2012, 2014; note that PVI values reported by Courson et al., 2013 are lower due to averaging data across two and three syllable words). While larger normative studies are warranted to estimate population variance and document any influences of factors such as age and sex, these data serve as a reference for determining when an individual has reduced contrastivity associated with a diagnosis of suspected AOS.

It is important to note here that we are not claiming reduced PVI_vowel duration values or equal stress production as pathognomonic of AOS. Equal stress also has been listed as a feature of ataxic and spastic dysarthria (Duffy, 2005). Problems with lexical stress production have also been reported in individuals with non-fluent aphasia, although the types of errors reported in these analyses have varied (e.g., omission or reduplication of syllables, stress assignment errors, phonemic stress in compound nouns versus adjective-noun phrases and degree of lexical stress contrastiveness) and the potential influence of concomitant AOS has not been clear (Balan & Gandour, 1999; Gandour et al., 1994; Howard & Howard, 1999; Niemi, 1998; Seddoh, 2004, 2008). The PVI appears useful for quantifying the percept of equal stress in polysyllabic words, and possibly in connected speech (Low et al., 2000) and may find use in investigations of different aspects of stress production among people with AOS, aphasia and dysarthria. Tracking PVI over time may also provide an objective quantitative measure of prosody intervention effects or degradation of prosody in neurodegenerative conditions.

The normal stress contrastiveness found for peak intensity of the vowel is consistent with the perception that intonational patterns (i.e., intensity and f_0) within words and phrases is relatively intact in individuals with AOS and more broadly in individuals with left hemisphere damage (Alcock et al., 2000; Niemi, 1998; Sidtis & Van Lancker-Sidtis, 2003; Zatorre & Belin, 2001). We did not measure f_0 here as previous work had suggested that f_0 contour varies for several reasons, over and above expression of lexical stress (Ballard et al., 2012) Nonetheless, more systematic analysis of ability to vary intensity and f_0 within brief segments of speech is still required. If it remains consistent, that control of relative durations is the primary problem underlying the perception of equal stress in AOS, then it is possible that impairment-based treatment exercises should focus on developing control of relative timing across syllables within words and/or sentences and rapid smooth transitions between syllables (e.g., Ballard et al., 2010; Brendel & Ziegler, 2008) rather than other tasks that might focus on varying intensity and pitch, such as emphatic stress tasks (Wertz, LaPointe, & Rosenbek, 1984).

Several studies have suggested that linguistic complexity of an utterance influences various production parameters (Strand & McNeil, 1996; Walker et al., 2009). Strand and McNeil (1996) reported that individuals with AOS had longer vowel durations during the production of phrases as compared to multisyllabic words and monosyllabic words. It is possible that the difference in linguistic complexity from the isolated word to the sentence condition was responsible for the greater difficulty in lexical stress production in the latter condition for participants with AOS. However, the carrier sentence was linguistically simple and constant across both SW and WS trials (i.e., "Here is the [word]"). Perhaps a more likely explanation is that the weak syllable "the" preceding the weak onset to the multisyllabic word increased the time pressure for rapid transitioning between syllables. Despite instructions and reminders to produce the sentences without pauses between words, and the prior exposure to the target words in the isolated word condition, individuals with AOS frequently were perceived to hesitate prior to the target word. This suggests that the sentence condition was challenging from a motor planning/programming perspective.

Our data do not support the findings of studies such as Walker et al. (2009) that individuals with aphasia without AOS have altered production of lexical stress, at least as it was measured here. Our aphasia-only group were not differentiated from the healthy controls on the measures tested. This supports the use of acoustic measures and indices such as PVI_vowel duration to differentiate between subgroups of individuals with left hemisphere damage, namely individuals with AOS (with/without aphasia), and individuals with aphasia only. It further suggests that this task and measure of lexical stress production is tapping into the motor planning/programming impairment of AOS, rather than any linguistic impairment with representation or planning of stress.

Finally, we attempted to measure receptive prosody to determine whether any differences across groups in production might be related to impaired perception. The results of the PEPS-C test indicated that both the APH and AOS groups had greater difficulty, to a similar degree, than most healthy participants in interpreting prosodic cues in the PEPS-C tasks. This suggests that performance in these types of receptive prosody tasks does not explain the observed differences between the patient groups. As reported by Peppé (2009), dysprosody is an area that has not been widely investigated, especially the comprehension of prosodic cues. Further investigation is essential to extend knowledge on receptive prosody skills of people with AOS (with/without aphasia) and aphasia only and to understand the relationship between receptive and expressive prosody skills in these disorders. Such endeavours will undoubtedly lead to more sensitive measures of receptive prosody.

LIMITATIONS AND FUTURE DIRECTIONS

The small sample size for the groups and the restricted range of AOS severity in the present study may have precluded trends in some experimental conditions from reaching significance. Further research involving a larger group of participants is warranted to replicate the current findings and more firmly establish their diagnostic sensitivity for individuals with AOS who are able to attempt three syllable word production.

In order to further investigate the impact of the motoric demands of the stress pattern versus the typicality of the stress pattern on production, future studies may include verbs with strong–weak versus weak–strong stress patterns. For English verbs, the weak–strong pattern is more frequent than the strong–weak. If the effects observed here are associated with weak syllable onsets, then individuals with AOS should show abnormal relative vowel durations for vowels with weak–strong stress pattern, as they do for nouns with this stress pattern; if the effects are associated with the frequency of the stress pattern for a given set of words, or grammatical class, then they should show abnormal relative vowel durations for the less frequent strong–weak stress pattern in verbs, in contrast to nouns. In addition, the use of a consistent carrier phrase during the declarative task allowed for comparison of the acoustic measures marking lexical stress across the participants and across the three different groups. However, these tasks may not reflect the use of prosody in natural situations (Walker et al., 2009).

CONCLUSION

The broad agreement in the clinical community that dysprosody is a common feature of AOS and the relative ease of measuring dysprosody acoustically make this a suitable place to begin looking for acoustic measures that may support diagnosis of AOS, particularly when it co-occurs with aphasia. The novel contribution of this study is that we have identified a simple task and a simple acoustic measure of duration contrastiveness that has potential for development as (a) an easily implemented diagnostic tool to complement perceptual ratings and (b) a measure of treatment-related change that is more robust to factors such as perceptual drift and unaided clinician judgment (Kent, 1996). This study indicates that individuals with AOS (with/without aphasia) produce appropriate stress patterns in three syllable strong–weak and weak–strong words. However, the magnitude of durational contrastiveness for weak–strong words tends to be reduced compared to individuals with aphasia alone or healthy adults. Further, this difference is more pronounced in the more demanding context of sentence production versus isolated word production. We propose that this reduction in durational contrastivity underlies the commonly reported perception of equal stress in AOS, suggesting that impairment is not uniform but influenced by factors such as prosodic structure. The restriction of the stress production difficulty to weak–strong words, particularly when preceded by another weak syllable in sentences, suggests that the primary problem is in producing very brief segments that challenge the mechanism to reach articulatory targets for the current syllable or reduce the time available for retrieval and programming of movements for the upcoming syllable. Here, a within-word relative measure of vowel duration shows promise for guiding diagnosis and detecting AOS in individuals with aphasia. Further study will determine the robustness of this measure as a contributor to increasing diagnostic accuracy. Regardless, this represents an important step towards development of acoustic diagnostic measures that can support perceptual judgments of the presence of AOS, particularly for clinicians and researchers who are less experienced with this population.

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