CLINICAL LINGUISTICS & PHONETICS, 2002, VOL. 16, NO. 6, 461–483

Coarticulation patterns in children with developmental apraxia of speech

LIAN NIJLAND†, BEN MAASSEN†,
SJOEKE VAN DER MEULEN‡,
FONS GABREËLS§, FLORIS W. KRAAIMAAT¶
and ROB SCHREUDER#

†Dept. of Paediatric Neurology/Medical Psychology; University Medical Centre Nijmegen, The Netherlands
‡University Hospital Utrecht / Wilhelmina Children's Hospital Utrecht, The Netherlands
§Dept. of Paediatric Neurology; University Medical Centre Nijmegen, The Netherlands
¶Medical Psychology; University Medical Centre Nijmegen, The Netherlands
#Max Planck Institute for Psycholinguistics, Nijmegen, The Netherlands

(*Received 1 February 2002; accepted 27 May 2002*)

Abstract

The aim of this study was to enhance our insight into the underlying deficit in developmental apraxia of speech (DAS). In particular, the involvement of planning and/or programming of speech movements in context was tested by analysing coarticulatory cohesion. For this purpose, second formant frequency measurements were conducted in repetitions of nonsense utterances ([əCV] C=/s,x,b,d/; V=/i,a,u/), and compared across nine children with DAS, six normally speaking (NS) children and six adult women. The results showed both intra- and intersyllabic anticipatory coarticulation in NS children and adult women, in which the intersyllabic coarticulation was stronger in NS children than in adult women. The children with DAS showed more variability as compared to NS children, made, on average, less distinction between the vowels, and showed individually idiosyncratic coarticulation patterns. These results are discussed in the light of a delay as well as a deviance of speech development in children with DAS.

Keywords: Coarticulation, developmental apraxia of speech, planning, programming, acoustics.

Introduction

Developmental apraxia of speech (DAS) is an impairment that leads to a serious communicative disability. There is debate in the speech literature regarding specific

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Address correspondence to: Lian Nijland, Medical Psychology/Dept. of Paediatric Neurology, University Medical Centre St. Radboud, P.O. Box 9101; 6500 HB Nijmegen, The Netherlands. e-mail: l.nijland@cukz.umcn.nl

Clinical Linguistics & Phonetics
ISSN 0269-9206 print/ISSN 1464-5076 online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/02699200210159103

characteristics of DAS. Early research was mainly focused on the phonemic descriptions of the erroneous production of children with DAS. Since the end of the 80s more phonetic research has been conducted to study underlying processes (e.g. Hall, Jordan and Robin, 1993). In the present study we attempt to gain more insight in the underlying deficit of DAS by measuring the phonetic coarticulation effects in correctly produced utterances.

Characteristics of DAS

There has been much discussion about the issue whether DAS can be seen as a diagnostic entity. One of the main issues is the overlap between DAS and other speech disorders. McCabe, Rosenthal and McLeod (1998) found that many characteristics regarded as diagnostic for DAS also occur in the general speech-impaired population. The debate continues because attempts to find a diagnostic marker specific for DAS, up to now have not been successful (Shriberg, Aram and Kwiatkowski, 1997). Despite the overlap with other speech disorders and diagnostic difficulties, there is agreement about some of the more central or core characteristics of DAS. The speech is often unintelligible due to a large number of phonemic speech errors (substitutions and omissions) and articulatory abnormalities. These speech errors are inconsistent and the number increases with increasing complexity and length of the utterance. Spontaneous speech production is generally more disrupted than imitative speech. The most salient speech characteristics of children with DAS are: largely unintelligible speech, sequencing errors, abnormal prosody, high consonant error rates, many context-related substitutions, groping, and inconsistency of errors (Hall, Jordan and Robin, 1993; Thoonen, Maassen, Wit, Gabreëls and Schreuder, 1996). Non-speech actions, like coughing, chewing and swallowing, do not necessarily cause difficulties.

The number of studies concerning DAS is much smaller than the amount of studies about apraxia of speech in adults (AOS). Although both disorders arise from different origins, and there are differences between the speech characteristics of AOS and DAS, on the methodological level much can be learned of the study of the one compared to the other. Most research on AOS in adults and DAS has been conducted on the basis of perceptual evaluations, i.e. phonemic descriptions of segmental speech errors, which can be extended with analyses on the feature level (Thoonen, Maassen, Gabreëls and Schreuder, 1994; Forrest and Morrisette, 1999). However, perceptual analyses have their methodological limitations. The relatively subtle phonetic differences (for example tongue displacement) remain inconspicuous in perceptual evaluations. Instrumental analyses provide quantitative, objective data on a wide range of different speech parameters that go beyond the scope of an auditory-based judgement (Hardcastle and Edwards, 1992), as was shown in studies on the acoustic characteristics of the speech of subjects with AOS. Results showed that subjects with AOS differed from normally speaking subjects in voice onset time distribution by compression of the two categories of voiced versus voiceless stops (Freeman, Sands and Harris, 1978; Itoh, Sasanuma, Tatsumi, Murakami, Fukusako and Suzuki, 1982; Hoit-Dalgaard, Murry and Kopp, 1983), in longer word and vowel durations with prolongation of transitions, steady states, and intersyllabic pauses (Caligiuri and Till, 1983; Collins, Rosenbek and Wertz, 1983; Kent and Rosenbek, 1983), and in reduced intensity variations (Kent and Rosenbek, 1983). In contrast to AOS, only few studies report acoustic characteristics of developmental apraxia of speech. As a consequence, very little is known of the phonetic details of the speech of children with DAS.

Coarticulation

What is the underlying deficit in DAS? Several speech characteristics suggest that the underlying deficit should be found in an impairment of planning and/or programming of speech movements in context. From a motor perspective the articulatory unit is not a single phonemic segment, which means that the phonemic motor patterns are not invariant. Rather, successive articulatory gestures are highly dependent on the phonemic context and extend across phonemes, which results in articulatory overlap or coarticulation (Browman and Goldstein, 1992). If a segment influences a following segment this is called perseveratory coarticulation and an upcoming segment influencing a preceding segment is called anticipatory coarticulation. In this motor view, problems in planning and programming of speech movements leave their traces in the coarticulatory cohesion of the utterances. Hertrich and Ackermann (1995), for example, found that in normal speech slowed speech rate resulted in a decrease of perseveratory coarticulation and, against their expectations, unaltered or even increased anticipatory coarticulation. From this, they suggested that different mechanisms underlie anticipatory and perseveratory coarticulation. Thus, coarticulation measurements yield valuable data regarding speech motor processes. Therefore, in the present study we investigated the nature and amount of anticipatory coarticulation in utterances of children with DAS in order to determine a problem in planning and/or programming of speech.

Although hardly any research was done on coarticulation patterns in children with DAS (e.g. Sussman, Marquardt and Doyle, 2000), studies on coarticulation in AOS in adults are mentioned frequently. These studies have reported divergent results. Whereas some researchers found a lack of coarticulatory cohesion in apraxic patients (Ziegler and Von Cramon, 1985, 1986; Dogil, Mayer and Vollmer, 1996; Whiteside and Varley, 1998), others did not (Katz and Baum, 1987; Katz, 1988). The data of Southwood, Dagenais, Garcia and Sutphin (1996) showed that speaking rate and articulators involved might be one of the sources of the different coarticulation patterns in apraxic speech (delayed coarticulation at fast rates and labial coarticulation). Furthermore, divergent problems underlying AOS were suggested, varying from inappropriately phasing speech gestures (Ziegler and Von Cramon, 1985, 1986), and lack of automation (Whiteside and Varley, 1998), to phonological overspecification (Dogil *et al*., 1996).

In order to overcome interpretation problems due to differences in speech tasks and material, the design of the present study included both lingual and labial consonants and besides the research group, children with DAS, also two control groups were included (normally speaking children and adult women). Considering the divergent results on AOS, we might expect either *weaker* or *stronger* coarticulation in children with DAS as compared to normally speaking children, in the present study. On the one hand *weaker* coarticulation could be predicted in DAS based on the frequently reported slow and protracted speech, due to a protracted segment-to-segment motor planning or programming. This would result in a lack of coarticulatory cohesion. On the other hand, *stronger* coarticulation effects (more influence of upcoming vowel on preceding sounds) could be found in the speech of children with DAS as a result of a more global planning of the utterances, under the hypothesis that motor control is not fully developed. If such were the case, then DAS speech would resemble the speech of younger, normally speaking children, which is characterized by stronger coarticulation (Nittrouer, Studdert-Kennedy and McGowan, 1989; Nittrouer, 1993; Nittrouer, Studdert-Kenedy and Neely, 1996).[1] Furthermore, in the present study, it is considered whether these coarticulation effects are restricted to the sounds within the syllable, called 'intrasyllabic coarticulation', or extend across the syllabic boundary, 'intersyllabic coarticulation' (Boers, Maassen and van der Meulen, 1998). The above-mentioned pathological and developmental studies on coarticulation will be discussed in more detail in the Discussion, together with the findings of the present study.

The methods adopted in the present study were derived from the studies of Nittrouer and colleagues (Nittrouer *et al*., 1989; Nittrouer, 1993; Nittrouer *et al*., 1996). In [əCV]-utterances we measured the influence of the vowel V on the preceding consonant C (intrasyllabic coarticulation), and on the schwa [ə] (intersyllabic coarticulation). Three different vowels (/i, a, u/) were chosen that are the extreme vowels in the Dutch vowel space. These vowels are distinctive in second formant (F2) frequency value. The influence of the vowel on preceding segments (anticipatory coarticulation) was determined by measuring the F2 values throughout the utterance. The coarticulation patterns (the F2 patterns) of children with DAS were compared to those of normally developing children.

Thus, the question for this study was, does the speech of children with DAS show weaker or stronger coarticulation as compared to normally speaking children? And, if so, are these effects restricted to the syllable (intrasyllabic) or do they cross the syllable boundary (intersyllabic)?

Method

Participants

The acoustic analyses were rather time consuming, therefore only nine children with DAS and six NS children were analysed. We decided to analyse a greater number of children with DAS than NS children, since their individual patterns were expected to be more diverse. The participants were randomly taken from 19 children with DAS (14 boys and five girls between the age of 4;11 and 6;10) and 19 NS children (matched for sex, age and dialect region). All children were native speakers of Dutch.

The children with DAS were selected from special schools for children with speech and language disorders. Speech-language pathologists of these schools referred 70 children diagnosed as having dyspraxic speech problems to us. Based on samples of spontaneous speech, repetitive imitations of words and brief phrases, and a diadochokinetic task (collected by the school speech-language pathologist) the following selection criteria were adopted: exhibiting many phonemic errors despite a complete phoneme repertoire, high frequency of consonant substitutions (and omissions in clusters), sequencing difficulties of phonemes and syllables, inconsistent error patterns, and inability to produce complex phonemic sequences (Hall *et al*., 1993; Thoonen *et al*., 1996). To the selection of 29 children from the larger group of 70 children the following tests were administered: assessment of hearing level, a language comprehension test (the Dutch version of the Reynell Developmental Language Scales (Reynell and Huntley, 1985; Bomers and Mugge, 1989)), and speech tasks developed by Thoonen *et al*. (1996). Furthermore, it was established that the children did not exhibit organic disorders in the orofacial area, gross motor disturbances, dysarthria, or below-normal intelligence. Based on the test results, another 10 children were excluded because of hearing problems and poor language comprehension (test score 1 standard deviation or more below average). The remaining 19 children can be considered as ‘clear’ cases of DAS.[2]

In previous studies we found that the speech of children with DAS is particularly characterized by (1) a high consonant substitution rate, which is not only high in nonsense utterances but (2) also in meaningful speech, and (3) difficulty with the Maximum Repetition Rate task on tri-syllabic sequences (‘pataka-pataka…’) as compared to mono-syllabic sequences (‘papa…’, ‘tata…’, ‘kaka…’) (Thoonen *et al*., 1994; Maassen, Thoonen and Boers, 1997). Therefore, these parameters were extracted from the speech material collected from the administered speech tasks. (For the exact procedure of administering this assessment the reader is referred to Thoonen *et al*., 1996.) The results are presented in table 1. The percentages consonant substitution of singleton consonants on syllable initial position (‘Subst’), and from these the percentage of substitutions with respect to place-of-articulation (‘Substpl’), were derived from an imitation task of meaningful (first two columns of table 1) and nonsense utterances (third and fourth column of table 1). Maximum Repetition Rates (MRR), expressed in mean number of syllables per second, are given for the monosyllabic (the average of the three target monosyllable utterances, ‘papa…’, ‘tata...’, or ‘kaka...’) and trisyllabic (‘pataka...’) sequences in columns five and six.

Table 1. *Individual scores on the selection tasks (percentage consonant substitution in meaningful and nonsense word-imitation task and mean number of syllables per second in Maximum Repetition Rate task), and on the experimental task (percentage correctly produced utterances) in children with DAS and normally speaking children (NS)*

		Meaningful		Nonsense		MRR		
DAS	Age	Subst	Substpl	Subst	Substpl	Mono-syll	Tri-syll	% correct
#1	5;0	26%	76%	47%	68%	3.53	1.93	82
#2	5;1	24%	56%	64%	79%	4.12	3.38	89
#13	5;6	22%	71%	38%	68%	3.64	2.21	64
#14	5;7	15%	60%	15%	30%	4.63	3.68	96
#17	5;10	17%	64%	67%	70%	4.63	Unable	89
#20	5;11	30%	60%	48%	72%	3.31	Unable	61
#21	5;11	31%	85%	–	–	3.20	Unable	96
#28	6;10	40%	60%	39%	96%	4.23	3.61	57
#29	6;10	14%	56%	15%	60%	3.98	Unable	86
NS	Age	Subst	Substpl	Subst	Substpl	Mono-syll	Tri-syll	% correct
#54	4;9	7%	0%	12%	38%	4.29	3.52	90
#36	5;0	0%	0%	17%	64%	4.85	3.68	92
#42	5;3	3%	0%	6%	25%	4.74	4.05	93
#53	5;6	8%	0%	8%	20%	4.49	5.03	100
#58	5;6	5%	33%	9%	33%	4.44	5.08	96
#49	5;11	1%	0%	13%	0%	4.97	3.06	100

Note. Subst: percentage substitution of singleton consonants on syllable initial position. Substpl: percentage substitution of place relative to the number of substitions (Subst). Mono-syll: mean number of syllables per second of monosyllable utterances (/pa/, /ta/, /ka/). Tri-syll: MRR in a tri-syllable utterance /pataka/.

In case the child was not able to produce five successive trisyllabic sequences correctly, even after several attempts, this is indicated with 'unable'. The data in the last column of table 1 are explained below. The percentages consonant substitution and the MRR scores clearly distinguish the two groups: the children with DAS showed higher percentages consonant substitution—remarkable are the percentages substitution in meaningful utterances and the substitution of place—and smaller MRR scores as compared to the NS children.

Apart from the children, also six adult women were analysed. They functioned as a reference of the end stage of normal development, were all between 20 and 30 years of age, and had no history of speech pathology, orthodontics, and hearing problems. We opted for women because, rather than male voices and vocal tracts, female voices and their vocal tracts are more similar to those of children.

Speech material

The speech samples consisted of disyllabic nonsense utterances of the type [əCV], in which V was one of the extreme vowels /a, i, u/ of the Dutch vowel space, and C was either a fricative (the alveolar /s/ or the velar /x/) or a stop (/b/ or /d/). These utterances are comparable to the speech material of Nittrouer *et al.* (1989, 1993, 1996). However, in contrast to the alveolar-palatal distinction in the fricatives /s/ − /ʃ/ used by Nittrouer *et al.* (1989, 1993, 1996), the alveolar-velar distinction /s/ − /x/ was used in this study. The reason for this choice was that the articulatory positions are further apart, and the fricative /x/ is very common in Dutch, in contrast to /ʃ/. We decided to use voiced stops (/b, d/).[3] The reason for this is that formant transitions can be determined better in voiced stops as compared to voiceless stops (Blumstein and Stevens, 1979). To compare the results of the stops with the fricatives on place of articulation, it would have been better to use the voiced stops /d/ and /g/. However, the /g/ does not occur in Dutch (only as a result of assimilation, or in loan words).

All items were spoken in the same carrier phrase, 'he de …weer' [hed … wI:r] ('hey the … again'), and repeated six times, so in the end each child produced 72 utterances (three vowels * four consonants * six repetitions). Sometimes children (especially the children with DAS) were not able to correctly produce an utterance. In that case a second attempt was made immediately after the first. A unidirectional dynamic microphone mounted on a headset (Shure SM10A) and a tape-recorder (Kenwood KX54) were used to record the speech samples. The headset kept the microphone at a constant distance of 5 centimetres in front of the right corner of the subject's mouth.

Acoustic analyses

Selection and digitizing

The speech samples were digitized with a sample frequency of 25 kHz and the relevant sections (i.e. schwa-C-V segments) were spliced out, using the Kay Elemetrics Computerized Speech Lab (CSL) analysis system, Model 4300B. During the sampling procedure, utterances of which the [əCV]-part was phonemically incorrect were skipped. This led to a reduction of the number of repetitions, never to a total absence of an utterance type. Although the reliability of this selection procedure was not formally tested, it was subject to consensus discussion during the determination of the reliability of the measurement procedure (see below). In the last column of table 1 the percentages of correct utterances per child are given, which show that children with DAS produced more phonemically erroneous utterances than NS children. For seven out of nine children with DAS the percentages correct were below 90%; all NS children produced between 90% and 100% correct.

As a first step in the acoustic analyses, information of the oscillogram, FFT-spectrogram, and energy window was used to determine the onset and offset of each segment (schwa, consonant, and vowel),[4] and markers were set at the segments' onsets and offsets and at the plosive burst, using indications given by Nittrouer (1993). Inter-observer agreement concerning the placing of these markers was tested in a subset of the data. For this purpose, three observers independently placed markers in the 72 utterances of two children, namely one child with DAS and one NS child. High correlation coefficients were found (from 0.78 to 0.99 over all markers), which indicates a significant reliability between the observers. The mean difference in marker position over all markers was 12.2 ms (SE = 2.8 ms), which was larger in the utterances of the child with DAS (mean = 17.2 ms; SE = 5.6 ms) than in the utterances of the NS child (mean = 7.6 ms; SE = 0.9 ms). The markers at the onset and offset of the segments were used to determine F2 values at particular locations throughout the utterance.

Formant extraction

The second formant (F2) trajectory was used to determine the differences between utterance types. In the voiced sections of the signal (i.e. schwa and vowel) the CSL-program automatically positioned impulse markers just before a major amplitude peak and at a positive zero crossing (equals the closing of the glottis during voicing). However, sometimes this automatic placing was not accurate. Whenever necessary, the wrongly placed impulse markers were corrected interactively. After this, the formant values (with corresponding bandwidths) were obtained using pitch-synchronous Linear Predictive Coding (LPC) analyses (triangular analysis window; 20 components autocorrelation with pre-emphasis of 0.950). F2 values were extracted at five locations in the schwa and vowel: at schwa-midpoint (1) and schwa-offset (2), at the vowel transition onset (3) and at transition end (4), and at vowel midpoint (5). A separate LPC-analysis was performed on a Hamming window of 20 ms in the consonant (6) in accordance with Nittrouer (1993); in the fricatives the measurement window was centred at 20 ms before offset; in the plosives the start of window was at the plosive burst.

Measuring the first and second formant frequencies is quite hard in children's and female voices due to the high fundamental frequencies (Bennett, 1981). Therefore, a post-processing procedure was followed to reject invalid formants. For each of the four relevant vowels (schwa, /i/, /a/, /u/) lower and upper limits for the first (F1) and second formant (F2) were determined by inspection of the LPC-based formant values plotted as dots over the FFT-spectrograms. Only formant values that fell within the black regions in the spectrogram were accepted as valid. The mean midpoints and widths of the ranges for each vowel and group of speakers are presented in table 2. These ranges are quite large due to inter-speaker differences. Because of these large inter-speaker differences, upper and lower limits were determined for each individual speaker separately. These upper and lower limits were used in the next analysis step. To determine whether the frequency values, obtained

Table 2. *Mean midpoints and width of ranges of F1 and F2 (in Hz) in the schwa and vowels of each group*

	Children with DAS		NS children		Adult women	
Utterance	Schwa	Vowel	Schwa	Vowel	Schwa	Vowel
[əCa]–F1	659; ±351	945; ±543	570; ±253	905; ±543	431; ±155	730; ±370
F2	2396; ±853	2049; ±618	2201; ±698	2005; ±597	1988; ±378	1761; ±423
[əCi]–F1	648; ±339	567; ±261	538; ±238	532; ±232	402; ±133	381; ±131
F2	2463; ±830	2845; ±712	2206; ±441	2695; ±700	2186; ±418	2569; ±473
[əCu]–F1	618; ±283	573; ±268	573; ±273	502; ±202	400; ±136	470; ±205
F2	2283; ±945	1652; ±894	2084; ±787	1483; ±880	1980; ±503	1118; ±600

Note 1. Ranges for schwa were determined separately for each utterance type, resulting in minor differences depending on the upcoming vowel.
Note 2. Ranges displayed here are rather broad, which reflects the differences between speakers within and between groups. Precautions were taken to find the 'correct' formant within the ranges (see text).

with the LPC-analyses, fell within the range defined in the preceding step and thus could be considered the first and second formant, a computer-program was developed for post-processing. The post-processing procedure was conducted per analysis-frame, i.e. per impulse marker.

As a first step in the post-processing procedure the frequency values were sorted from low to high, and all formants with a bandwidth higher than the predetermined maximum bandwidth, which was fixed at 600 Hz, were eliminated. In the next step it was decided whether the remaining formant values fell within the F1- or the F2-ranges. If a value was found within the F1-range, this value was accepted as valid F1 value. In case more than one value was found, the higher one was taken, in order to be sure that F0 was not mistaken for F1. At the same time, the lower limit of the F2-range was shifted downward (in the current analysis frame) to the found F1. In the same way, a formant frequency within the F2-range was accepted as valid F2 value. If more than one formant fell within the F2-range, the lower one was taken, in order to avoid mistaking F3 for F2.

The small variance of second formant values that was found in the repeated utterances of the adult women and of the NS children (which will be discussed later in table 3), made us conclude that the procedure was quite reliable. Measurement of the first formant frequencies resulted in many missing values, since the distinction between the fundamental frequency and the first formant could not always be made appropriately. Also in the second formant frequency measurement using this procedure suffered from missing values. However, the percentage of accepted F2 values was similar across the three groups, viz. the smallest was found in the consonant (DAS 73%; NS 80%; AW 66%) and the largest at vowel midpoint (DAS 99%; NS 99%; AW 94%).

Large inter-speaker variance in mean formant values was expected, partly due to anatomical differences between speakers. To correct for this variability, as a means of speaker normalization, formant *ratios* were calculated for each child separately. For each consonantal context, the formant values (of 6 repetitions) of utterances with /i/ were averaged and divided by the averaged formant values of utterances with /u/ (i/u-ratio).[5] Figure 1 gives a stylized example of a formant pattern and the calculated ratio-pattern. These ratios reflect F2-distinctions between the utterances. Typically, large ratios are found at vowel midpoint, where the distinction

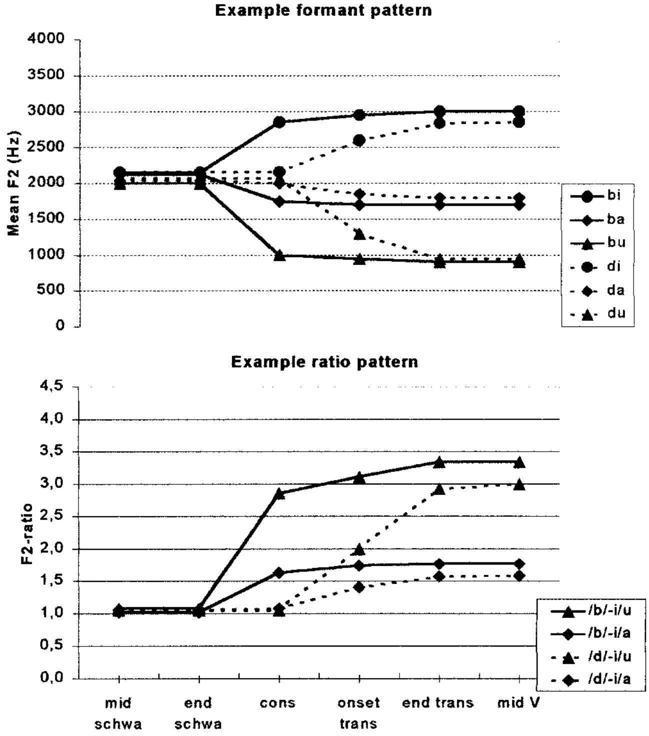

Figure 1. *A fictitious example of the pattern of F2-values throughout the utterance (upper figure) and the calculated ratios.*

between the utterances is at maximum. Smaller ratios close to unity, such as typically found in the schwa, reflect that F2 values are similar despite differences in the upcoming vowel. Thus, the higher the ratio is above 1 the more distinction there is between the utterances at that particular location.

Statistical design

In order to evaluate the statistical significance of formant value differences, analyses of variances were conducted first. However, parametric testing was not justified, because for most contrasts Levene's test for homogeneity of variance turned out to be significant (Winer, Brown and Michels, 1991). Therefore, nonparametric tests were conducted. Another way to solve this problem of heterogeneity is to aggregate the repeated utterances, resulting in average formant values of each utterance type per child. Subsequently, F2 ratios were calculated and an analysis of variance was performed on the obtained data. Eta-square (η^2) was calculated to determine the effect size of the analyses of variance. In order to test whether the F2 ratios were significantly higher than 1, a one-sample *t*-test was performed.

Results

In this section, before presenting the results of formant frequency measurements, the variability will be given. Above, in table 1, it was discussed that the scores of MRR and the percentages correct utterances of the children with DAS were more variable than those of NS children. Therefore, the variability within and between speakers per group is expected to provide valuable data. In table 3 the standard deviations of the formant frequencies are given, subdivided in variability attributable to the between subject factor 'Speaker' and the within subject factors 'Type' (utterance type) and 'Error' (the variability within speakers that is not attributable to the vowel or the consonant, but to the repetition of the same utterance). *F*-ratios were calculated to determine the significance of the difference in variance (viz. the square of the standard deviation presented in table 3) between the groups (F (factor) = var. $(\text{factor})_a$/var. $(\text{factor})_b$).

For all groups, the variances (viz. the square of the standard deviation presented in table 3) attributable to the factor 'Type' (utterance type) increased from the measurement point 'mid schwa' to 'mid V', whereas the variance of the factor 'Speaker' and the 'Error' variance decreased (although not monotonically). In particular these last variances were of interest, because they expressed the variability between and within speakers that is not attributable to the vowel or the consonant in the utterance (utterance type). *F*-ratios showed that these within speaker variances (F (error) = var. $(\text{error})_a$/var. $(\text{error})_b$) were significantly larger for the NS children than for the adult women ($F(391{,}383) > 1.46$; $p < 0.05$). Moreover, the children with DAS showed significantly larger within speaker variances as compared to the NS children ($F(495{,}391) > 1.70$; $p < 0.05$). In contrast, the between speaker variances (F(speaker) = var. $(\text{speaker})_a$/var. $(\text{speaker})_b$) did not differ significantly between the groups (DAS/NS: $F(8{,}5) < 5.61$; NS/AW: $F(5{,}5) < 1.97$; n.s.).

To summarize, it was found that the repeated utterances (error-variances) of the children were more variable than those of the adult women. The variability in children with DAS was even larger than in NS children. Although the variability within speakers differed significantly between the three groups (children with DAS

Table 3. *Variability of second formant frequencies expressed in standard deviations in Hz (square root of variance) for each group: children with DAS, normally speaking (NS) children, and adult women (AW), subdivided into variability attributable to between- (Speaker) and to within-subject factors (Type and Error) (including percentage of the factor variance in proportion to the total variance). Significance of difference between groups was determined by calculating* F *ratios*

Group	Factor	Df	Mid schwa	End shwa	Cons	Onset trans	End trans	Mid V
DAS	Type	11	976.69	1456.25	2890.49	3979.17	4442.50	4454.49
	Speaker	8	2246.91	2008.11	1265.63	1291.21	959.95	934.97
	Error	495	361.46	390.85	288.55	318.27	305.03	201.22
NS	Type	11	1071.56	1623.27	2829.20	3936.58	4454.49	4770.10
	Speaker	5	1144.82	848.12	710.12	971.80	934.97	977.02
	Error	391	196.18	215.66	216.23	216.62	201.22	154.24
DAS/NS[1]	*F* (error)	495;391	3.38*	3.28*	1.78*	2.16*	2.30*	1.70*
	F (speaker)	8;5	3.85	5.61	3.18	1.77	1.05	1.09
AW	Type	11	610.00	748.59	2196.55	3442.79	3614.72	4257.84
	Speaker	5	1467.08	1384.73	506.29	707.38	740.71	729.75
	Error	383	162.40	164.77	157.58	119.27	134.44	113.98
NS/AW[1]	*F* (error)	391;383	1.46*	1.71*	1.88*	3.30*	2.24*	1.83*
	F (speaker)	5;5	1.64	2.67	1.97	1.89	1.59	1.79

Note. Significance $*p < 0.05$, after Bonferroni's correction; [1] *F*-ratio = largest variance/smallest variance.

have the highest variability within speakers, AW the lowest), the variability between speakers within groups did not differ significantly.

Formant values and ratios

As a first result of the F2 patterns, it was found that the F2 values of the three groups differed significantly at all 6 measurement points (Kruskal-Wallis Chi-square $(df=2)>18.2$; $p<0.05$). The F2 values measured in the utterances of the children with DAS were higher compared to NS children (significantly at each measurement point except consonant and mid vowel: Mann-Whitney $Z>2.06$, $p<0.02$), which in turn were higher than those of adult women (significantly at all measurement points: Mann-Whitney $Z>2.11$, $p<0.02$).

Difference in overall F2 values, i.e. some speakers had systematic higher or lower frequencies than others, complicate the comparison between speakers and groups. To facilitate a more valid comparison, as was stated in the 'method' section, F2 ratios were calculated as a method of speaker normalization. For each speaker individually the formant values of utterances with /i/ were averaged and divided by the average formant values of utterances with /u/ (i/u-ratio). These ratios represent the distinction between the utterance types, i.e. the higher the ratio is above unity the more distinction there is between the utterance types at that particular measurement point. In figure 2 the i/u-ratios are presented throughout the utterance of the adult women (A), the NS children (B), and the children with DAS (C).

High ratios were found at the location 'mid V', in all three groups. Of course, high ratios here were expected; they just demonstrate that the vowels used in this study are characterized by different F2's. Children with DAS showed smaller i/u-ratios as compared to NS children and adult women ($F(2,79)=4.23$; $p<0.05$; post-hoc LSD DAS versus NS: mean difference $=-0.394$, $p<0.025$; NS versus AW: mean difference $=-0.040$, n.s.), which indicated that the distinction between the /i/ and /u/ was not as large in children with DAS as compared to the other groups. The more interesting part is formed by the ratios earlier in the utterance (all measurement points before Mid V), since these ratios indicate an effect of the upcoming vowel, i.e. anticipatory coarticulation of the vowel on the preceding schwa (intersyllabic coarticulation) and consonant (intrasyllabic coarticulation). Going from right to left, diminishing ratios can be observed in all figures (i.e. smaller ratios in the schwa than in the consonant), so there seemed to be diminishing effects from the upcoming vowel on the F2 values in the preceding consonant and schwa.

The ratio figures suggest that the strength of this anticipatory coarticulation was different for the different consonants (the dashed lines in figure 2 are closer to unity than the solid lines): the utterances with /d/ and /s/ showed weaker coarticulation than the utterances with /x/ and /b/ (in particular the /x/-utterances). An analysis of variance showed that the factor Consonant had a significant effect on the ratios of all measurement points in adult women and NS children (AW: F-values $(3,15)>5.62$; NS children: F-values $(3,15)>7.59$; $p<0.01$), and in children with DAS on all measurement points but two (end schwa and mid V). However, the effects were stronger in adult women and NS children than in children with DAS (NS: η^2: 0.60–0.89; AW: η^2: 0.55–0.89; DAS: η^2: 0.30–0.67). A striking feature in the figures of Adult women (2A) and NS children (2B) was the trajectory of the /x/-i/u ratio in the schwa and the consonant. These high /x/-i/u ratios were mainly

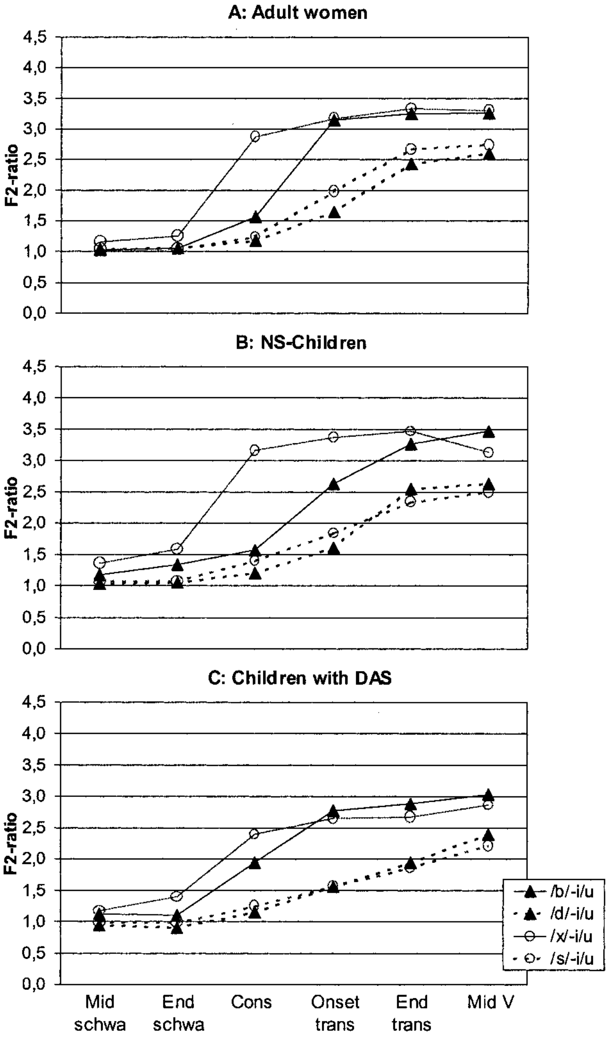

Figure 2. *F2-ratios of Adult women (A) and NS children (B), and children with DAS (C).*

caused by low F2 frequency in the /xu/-utterances, which was lower than all other /Cu/-utterances.

In order to evaluate the significance of the influence of the vowel on the preceding sounds (i.e. testing the null hypothesis that F2 ratios equal 1), one-sample *t*-tests were conducted for each speaker group separately (in order not to violate homoscedasticity) and each consonant separately. Results of these analyses are displayed in table 4.

The results in table 4 corroborate the patterns in the figures. In the consonant the F2 ratios are higher than 1 for all groups and consonant contexts (except for /b/-utterances in NS children), indicating intrasyllabic coarticulation. The F2 ratios in the schwa of adult women and NS-children were significantly higher than 1 (indicating intersyllabic coarticulation) for all utterances except the /b/-utterances in adult women. Comparing both groups, it was found that the ratios were higher

Table 4. *One sample* t*-test for each group (children with DAS, normally speaking (NS) children and adult women (AW)) and each consonant separately*

		Mid shwa		End schwa		Cons		Onset trans		End trans		Mid V	
Group	Cons	df	t	df	t	df	t	df	t	df	t	df	t
AW	/b/	5	0.56	5	0.87	4	4.36*	4	9.15***	5	10.10***	5	24.14***
	/d/	5	2.65*	5	3.26*	2	4.87*	4	15.03***	4	6.07***	5	12.88***
	/x/	5	4.77**	5	4.82**	5	8.42***	5	30.23***	5	12.17***	5	14.83***
	/s/	5	3.92*	5	4.30**	5	6.27**	4	5.16**	5	9.66***	5	14.09***
NS	/b/	5	4.06**	5	5.22**	4	1.87	5	6.48***	5	5.82**	5	8.17***
	/d/	5	5.04**	5	2.83*	5	8.21***	5	7.59***	5	12.20***	5	9.53***
	/x/	5	4.84**	5	4.77**	5	10.13***	5	10.28***	5	8.02***	5	10.42***
	/s/	5	2.85*	5	3.58*	5	5.37**	5	3.51*	5	9.48***	5	9.47***
DAS	/b/	7	1.20	5	1.26	6	3.77**	7	4.96**	7	7.86***	7	6.60***
	/d/	7	−0.06	7	−0.02	6	4.72**	6	2.91*	6	4.19**	7	5.56***
	/x/	8	2.01	8	2.28*	7	7.27***	8	6.99***	8	9.98***	8	8.16***
	/s/	8	1.32	8	1.22	7	5.08***	7	2.34*	8	3.24**	8	5.09***

Note. Significance $*p<0.05$; $**p<0.01$; $***p<0.001$.

in the schwa of NS children as compared to adult women (mid schwa $F(1,46)=4.67$; end schwa $F(1,46)=5.13$; $p<0.05$). This means that the intersyllabic coarticulation in NS children was stronger than in adult women. In children with DAS the *t*-test values were not significantly higher than 1 in the schwa, which means that no significant intersyllabic coarticulation effect of the vowel on the preceding schwa could be found in DAS. However, in the comparison of the ratios of the children with DAS to those of the NS children no group effect was found in the schwa and consonant, but only in the vowel (transition end $F(1,56)=6.23$; mid vowel $F(1,56)=4.42$; $p<0.05$). Thus, an explanation for the lack of significant results in *t*-test values in the schwa of children with DAS might lay in the high variability in DAS rather than in the absence of intersyllabic coarticulation.

To summarize the ratio patterns, in all three groups of speakers intrasyllabic coarticulation was found, the strength of which was dependent on the consonant (stronger effects in /b/- and /x/- compared to /s/- and /d/-utterances). Moreover, NS children and adult women showed intersyllabic coarticulation that was stronger in NS children than in adult women. No significant intersyllabic coarticulation could be found in children with DAS, which might be due to the high variability in DAS.

Individual speakers

As was discussed before, on the basis of the variances between and within speakers, children were more variable as compared to adult women. Furthermore, the children with DAS displayed more variability than the NS children did. Although no significantly larger between subject variances were found in the comparison of the NS children to the adult women, nor in the comparison of the children with DAS to the NS children, the individual ratio patterns showed different patterns among children, especially among the children with DAS. Therefore, the ratio patterns of the individual children are presented in figure 3 (A–O). In order to test the significance of the distinction between the /i/ and /u/-utterances Mann-Whitney tests were

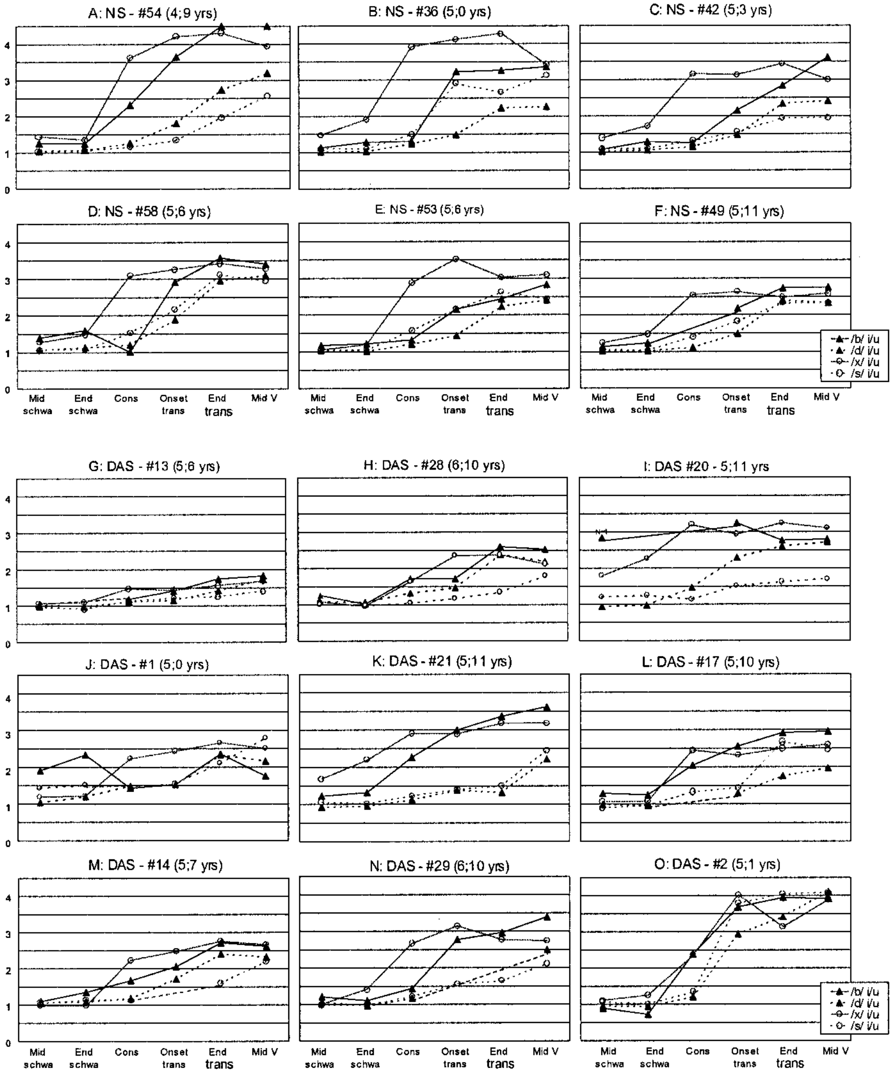

Figure 3. *Ratio-figures of the individual NS children (A–F) and the children with DAS (G–O).* Note. *NS children are ordered according to age; children with DAS according to similar patterns.*

conducted on the F2 values for each child and consonant separately.[6] Table 5 shows the consonant contexts in which significant differences between the F2 values of /i/- versus /u/-utterances were found, in the schwa (mid schwa or end schwa) and/or in the consonant.

Table 5 shows that almost all NS children had significant intrasyllabic coarticulation effects of the upcoming vowel on the consonant. Only in the /b/, we could not find significance since not enough valid values were available to compute the statistics. Every NS child did show a significant difference between /i/ and /u/-utterances measured in the schwa (intersyllabic coarticulation) in the /x/-utterances. Four of them reached significance in the /b/-utterances. The utterances with /d/ showed the least intersyllabic coarticulation; only two out of six children showed significant

Table 5. *Vowel coarticulation effects for preceding schwa and consonant as assessed by the differences between the F2-values of /i/-utterances and the /u/-utterances. A '+' indicates this difference was significant (determined by Mann-Whitney tests for each child and each utterance type (x, b, s, d) separately)*

		/x/-utterance		/b/-utterance		/s/-utterance		/d/-utterance	
Group	Child	Schwa	Cons	Schwa	Cons	Schwa	Cons	Schwa	Cons
NS	#54	+			+				+
	#36	+	+	+	1)	+	+		+
	#42	+	+		1)	+	+	+	+
	#53	+	+	+			+		+
	#58	+	+	+	1)	+	+	+	+
	#49	+	+	+	1)	+	+		
DAS	#13			1)					
	#28	1)	1)					+	
	#20	+	1)	1)	1)		1)		
	#1		+			+	1)		+
	#21	+	+	+	+		+	+	+
	#17		+	+	1)		+		1)
	#14		+	+	+	1)			+
	#29	+	+	1)			+	1)	+
	#2	+	+		+		+		

Note. 1) = not enough valid values to compute the statistic.

distinction between /i/- and /u/-utterances determined in the schwa. The ratio figures of the NS children (figure 3A–F) show that although the individual children differed in extent of coarticulation of the vowel (there appears to be a tendency for younger children displaying higher ratios) the pattern among the individual children was highly similar. The ratio figures (figure 3G–O) and statistical results (table 5) of the children with DAS display different and inconsistent patterns.[7] Some children with DAS showed very flat ratio curves, with very low ratios and hardly any differentiation in succeeding segments. Child #13 (figure 3G) is a striking example of this. The ratios were very low throughout the utterance. A similar pattern was found in child #28 (figure 3H), however the patterns showed slightly more differentiation in succeeding segments. Child #20 (figure 3I) also showed a pattern of flat curves, although the ratios are much higher. Remarkable are the high ratios in the schwa of the /x/-utterances, which displayed strong intersyllabic coarticulation. Child #1 (figure 3J) also exhibited rather flat curves. Still, intersyllabic coarticulation was found in the /s/-utterances and intrasyllabic coarticulation in the /x/- and /d/-utterances.

Child #21 (figure 3K) shows high ratios in the schwa (intersyllabic coarticulation) for the /x/- and /b/-utterances. In the utterances with /d/ and /s/ the transition to the vowel was made late in the utterance, just before vowel midpoint. Still, intrasyllabic coarticulation was significant in all utterance types.

Other children, Child #17, #14, and #29 (figure 3L–N) show more differentiation between succeeding segments, with weak intersyllabic coarticulation and strong intrasyllabic coarticulation, especially in the /x/-utterances.

Finally, the curves of child #2 (figure 3O) are divergent from the patterns of all other children. This figure shows very high ratios in the vowel that started either at transition onset (in the utterances with /s/ and /d/) or in the consonant (in the utterances with /x/ and /b/); even higher than was found in most NS children. Strong intrasyllabic coarticulation was found in the utterances with /x/, /b/, and /s/, but intersyllabic coarticulation was only found in the /x/-utterance. The ratios in the utterance with /b/ are even below unity.

To summarize the ratio results of the individual children, the patterns of the individual NS children showed more uniformity than those of the children with DAS. The utterances of children with DAS showed smaller F2 ratios throughout the total utterance (except for child #2, figure 3O) as compared to NS children, which represent less differentiation between the different utterances, and rather flat curves that indicate reduced acoustic differentiation between the successive speech segments.

Discussion

The question for this study was, can *weaker* or *stronger* coarticulation patterns be demonstrated in DAS as compared to NS children? And, if so, are these effects restricted to the syllable (intrasyllabic) or do they cross the syllable boundary (intersyllabic)? These questions were addressed by using formant frequency measurements. The first result was, that the variability of the formant values in the group of children with DAS was larger than in the NS children and in the adult women (see table 3). On the other hand, the variances between speakers within groups did not differ significantly across the three groups. As a second result, although both NS children and adult women displayed highly similar patterns of F2 ratios, NS children exhibited intersyllabic coarticulation in all utterances whereas adult women did not show intersyllabic coarticulation in /b/-utterances. In contrast to the NS children and adults, the children with DAS as a group made less distinction between the vowels (F2 ratios were lower at mid V, figure 2C). Furthermore, children with DAS produced idiosyncratic ratio patterns and therefore no significant intersyllabic coarticulation was found in this group of children.

Thus, the main result was on the whole less distinction between the vowels and more variability resulting in idiosyncratic patterns in children with DAS as compared to NS children and adult women. We will further elaborate the issue of normal and pathological speech and speech development below.

Normally speaking children versus adult women

Studies on the normal development of coarticulation show diverse results. Two opposite views are discussed here. The first view is represented by Nittrouer and colleagues (Nittrouer *et al.*, 1989; Nittrouer, 1993; Nittrouer *et al.*, 1996) and Siren and Wilcox (1995). In a series of coarticulation experiments Nittrouer *et al.* showed that in normal speech development a decrease in coarticulation between syllables (intersyllabic coarticulation: effect of V on preceding [ə]) was found earlier in development than a decrease in coarticulation within syllables (intrasyllabic coarticulation: effect of V on preceding C). Nittrouer *et al.* concluded that in development the phonetic segment is the endpoint rather than the starting point of development.

On the other hand, some researchers propagate the opposite view according to which during development the skill of syllable cohesion is learned after the child has mastered the articulation of the individual segments. From this perspective, the speech of children should reveal less evidence of coarticulation within and between syllables than the speech of adults. Evidence supporting this view comes from studies showing that anticipatory coarticulation (lingual and labial gestures) is more apparent in adults' than in children's utterances, both acoustically and perceptually (Kent and Rosenbek, 1983; Sereno, Baum, Marean and Lieberman, 1987; Sereno and Lieberman, 1987). Sussman, Duder, Dalston and Cacciatore (1999) found both weaker and stronger coarticulation effects in a single female child depending on the articulators involved. The divergent results found in studies investigating the development of coarticulation might be due to differences in methods and utterances used to study coarticulation.

In the present study the utterances of NS children exhibited stronger intersyllabic coarticulation effects than adult women's utterances as was shown in figure 2A and 2B (and in the statistical results). Intrasyllabic coarticulation was found in all utterances, but was weaker in utterances with alveolar consonants (/d/ and /s/) than in the utterances with /b/ or /x/. These results support the view of Nittrouer *et al.* that *more* coarticulation is found during development compared to adult speech. Furthermore, more variance was found in the repeated utterances of NS children as compared to those of adult women, which indicates inconsistency. This inconsistency can be interpreted as immaturity of the children's speech production system, in which the speech production process is not fully automated.

In summary, the results of this study support the idea that normal speech development leads to more consistency in repeated utterances and to smaller intersyllabic coarticulation effects. With this in mind the coarticulatory effects as found in the utterances of children with DAS will be re-examined.

Developmental apraxia of speech

Like developmental studies on coarticulation, studies on coarticulation in acquired apraxia also reported divergent results (Ziegler and Von Cramon, 1985, 1986; Katz and Baum, 1987; Katz, 1988; Dogil *et al.*, 1996; Southwood *et al.*, 1996; Whiteside and Varley, 1998). The conclusions of these studies varied from an absence of coarticulatory cohesion due to a lack of automation (Whiteside and Varley, 1998) to a preservation of coarticulation depending on articulators involved and speaking rate (Southwood *et al.* (1996) found distorted labial coarticulation at all speaking rates and distorted lingual coarticulation at fast speaking rate). Therefore, the design of the present study included both children with DAS and control groups (normally speaking children and adult women), in order to overcome interpretation problems due to differences in speech tasks and material.

In the comparison between children with DAS and NS children, as a first result, significantly larger variances in the repeated utterances were found in children with DAS as compared to NS children. This was not surprising, since high variability is often found in speech disorders (McCabe *et al.*, 1998). These larger variances, indicating inconsistency, can be interpreted as less mature automation. An explanation for the small number of significant differences in variance between speakers in children with DAS as compared to NS children could be found in the fact that only the phonemically correct utterances were used in the analysis. More variability might have been found if all utterances were considered for analysis. As a second result, the average F2 values of children with DAS were higher than those of NS children. As shown in table 2, not only F2 but also F1 values were, on average, higher in the DAS than in the NS group (this was not statistically analysed). Since the F2 is determined by the size of the front cavity (which is influenced by both the shape of the back of the tongue and liprounding) and the F1 is related to both jaw opening (F1 is higher when jaw opening is larger) and length of vocal tract (inversely proportional) an explanation for these group differences in F2 values does not seem to be straightforward (Zemlin, 1988). Furthermore, all three target vowels displayed such a group difference, which might be explained on the basis of differences in general size factor (due to anatomical differences such as growth rate) rather than behavioural aspects such as lip protrusion. However, this last explanation does not seem logical since there is no independent evidence for this and, moreover, the two groups of children were matched with respect to age. Thus, no convincing explanation was found for the group differences in F2 values.

Thirdly, average F2 ratios of children with DAS displayed less differentiation between utterance types, especially measured in the vowel, compared to the average F2 ratios of NS children. A reduction in vowel distinction (i.e. children with DAS do not make as much distinction between the different vowels) is expected to lead to less distinction between the utterance types measured earlier in the utterance, i.e. in the preceding consonant and schwa, which indicates a reduction of coarticulation. After all, the smaller the distinction between vowels, the less this effect can spread backwards to the preceding phonemes. The results of the individual children, however, suggest that a reduction of vowel distinction does not necessarily imply reduced coarticulation. The NS child #49 (figure 3F; table 5) displayed small distinction in the vowel, yet significant inter- and intrasyllabic coarticulation. And vice versa, an increase in vowel distinction does not necessarily lead to larger coarticulation effects; the DAS child #2 (see figure 3O and table 5) displayed a large distinction in the vowel, yet only significant intersyllabic coarticulation in the /x/-utterances. Because of this, the children were considered individually. These results showed inconsistent patterns among children with DAS. Some children displayed very flat curves (child #13, #28, #20, #1) with hardly any intra- and intersyllabic coarticulation. Another child (Child #21) showed large coarticulation effects in the /x/ and /b/ utterances, but very small coarticulation effects in the utterances with /d/ and /s/. Other children (child #17, #14, #29, and #2), however, showed more segmented speech with weak intersyllabic coarticulation. These divergent results contrasted with the consistent intrasyllabic coarticulation in the NS children.

Finally, a possible weaker intersyllabic coarticulation effect in children with DAS may be associated with difficulty in grading syllable stress (Shriberg *et al.*, 1997). If they produced the schwa as in a strong rather than as in a weak syllable, this strong syllable may be less 'susceptible' to influence by the upcoming vowel.

In conclusion, the F2 values in the utterances of the children with DAS can be characterized by (1) large variability, (2) higher F2 values, (3) lack of distinctiveness between the utterances, especially shown in the F2 ratios measured at vowel midpoint, (4) a smaller number of inter- and intrasyllabic coarticulation effects (although this might be due to lower statistical power), and (5) idiosyncratic patterns. The first result, larger variability was also found in the NS children as compared to the adult women. This can be interpreted as 'younger speech' characterized by less automation. Results of a follow-up study 1;3 years later might further test this hypothesis. The divergent patterns of coarticulation that were found in the utterances of the individual children with DAS, however, indicate that it is not merely a delay in speech. Each child has its own motor pattern to cope with the problems in the speech production process.

Homorganic versus heterorganic

Hardcastle and Edwards (1992) showed that the tongue could be considered as two separate articulators: tongue body and tongue tip/blade. The production of the velar fricative [x] involves the tongue body and the tongue tip is used for the alveolar [s]. Vowels are typically produced by the tongue body. As a consequence of this, as far as coarticulation is concerned, the critical difference between the different utterances is the number of articulators involved. Thus, [ᵊxu] and [ᵊxi] can be considered homorganic (consonant and vowel share the tongue body as articulator). On the other hand, the sequences [ᵊsu] and [ᵊsi] can be considered heterorganic (both tongue-articulators are involved: tongue tip/blade for [s] and tongue body for [u] or [i]). A similar distinction between homorganic and heterorganic occurs in the utterances [ᵊbu] and [ᵊbi]. In the homorganic [ᵊbu] consonant and vowel share one main articulator, the lips, for closing and rounding whereas in the heterorganic [ᵊbi] lip rounding is not necessary. Note that [ᵊbu] is a homorganic sequence with respect to a different articulator (lips) than [ᵊxu] (tongue body). In the utterances [ᵊdu] and [ᵊdi] the consonant and the vowel do not share the main articulators tongue body or lips.

A closer inspection of the F2 data yields additional, interesting results related to this homorganic and heterorganic distinction. The utterances with the alveolar consonants /d/ and /s/ showed smaller coarticulation effects, especially intersyllabic, than the utterances with labial /b/ and velar /x/ consonants. In the /b/-utterances this is mainly due to the influence of the vowel /u/ on the preceding sounds. This finding is compatible with the findings of Fowler and Brancazio (2000), who found differences in coarticulation resistance of consonants, in which the consonant /b/, /v/, and /g/ showed less resistance than the consonants /d, ð, z, ʒ/. If we think of coarticulation as competition for the same articulators, we might infer that consonant-vowel sequences that share the same articulator, i.e. are homorganic (e.g. lips in [bu]), cause articulatory movements to overlap more, resulting in stronger coarticulation effects, than consonant-vowel sequences that do not share the same articulator, i.e. are heterorganic (e.g. [si]). Nittrouer (1993) compared coarticulation in /k/ and /t/ contexts and concluded from stronger intersyllabic coarticulation in /k/ than in /t/ that '…the tongue was apparently freer to move in anticipation of the upcoming vowel in the /k/ context than in /t/ context.' (p. 967). Our data corroborated this difference between velar and alveolar for all groups of speakers. Thus, the factor homorganic versus heterorganic plays a consistent role in the extent in which coarticulation occurs.

The stronger intersyllabic coarticulation effects in NS children as compared to adult women for the utterance /ᵊbu/ suggest that the children who participated in this study had not yet developed an adult coarticulation pattern. Furthermore, it suggests that homorganic articulation patterns mature later than heterorganic articulations. The results of a second measurement (1;3 years later), to be presented in a following publication will reveal more data on coarticulation patterns in normal development.

Methodological issues

A methodological concern of this study bears upon the reliability and validity of formant analyses. It is well documented that formant measurements in women and children's speech is problematic (e.g. Bennett, 1981). Therefore, in the present study several precautions were taken to improve reliability and validity of the measurements. First, unequivocal criteria were established to segment the acoustic signals into speech sounds. In particular for the most relevant segments (schwa, consonant and vowel), onsets and offsets were clearly demarcated. In order to assess reliability two researchers segmented part of the speech material. It turned out that the inter-observer reliability was quite satisfactory. Second, two sources of information were used to determine formants. For each speaker several tokens of more than one utterance type were thoroughly inspected with respect to the correspondence between the Fast Fourier spectrogram and the LPC-determined formant values on the basis of the formant values plotted overlaid on spectrograms. From these inspections ranges of formant values for that particular speaker were assessed, which were later used to remove outliers. Moreover, *all* spectrograms and formant traces were visually inspected for erratic patterns. We are convinced having optimized the measurements by adopting such a speaker-adapted procedure. The low variability and low dropout rates of the utterances spoken by the adult women support the success of this optimization. Higher variances were found for the NS children, and even higher for the children with DAS. Although it is hard to distinguish increased variability in productions from increased measurement error, the thorough procedure used seems to warrant our conclusions. Besides this, as a consequence of this higher variability in children the power of statistical tests is smaller, which led to a smaller number of significant differences in vowels in table 5. Thus, seemingly large coarticulation effects as appears in the ratio figures of the individual children did not always reach significance in table 5.

An issue for implementation of these procedures for clinical assessment is the fact that the procedure described above is very time consuming. This forms a serious impediment for large-scale implementation. In a future study we aim at developing a more automatic measurement procedure.

A separate problem is the measurement of the second formant frequencies in the consonants, particularly the plosives. LPC-measurements in the plosive bursts frequently resulted in large formant bandwidths. Because of the strict criteria we used, many of these resulted in missing values. Much less problems were encountered in the fricatives, which corresponds to the results reported by Nittrouer *et al.* (1993, 1996). Currently, the spectral moments of these same utterances are measured (Maassen, Nijland and Van der Meulen, 1999). These will be compared to the formant frequencies.

Besides the method described in this study to show coarticulation, the method of determination of locus equations (described for example in Sussman *et al.*, 2000) was also executed. However, since the speech material was not constructed for this purpose, the small number of different vowels (only three instead of ten used by Sussman *et al.*, 2000) did not result in reliable slope calculation. Therefore, the results could not be interpreted reliably and were not shown here.

Final conclusion

To conclude, acoustical analysis of the speech of children with DAS, as was done in the present study, reveals phonetic deviancies as compared to normal speech that cannot be revealed by phonetic transcription or perceptual judgement. This helps to clarify the underlying problem of children with DAS. We realize that studying only children with DAS and no children with other speech disorders we cannot draw any conclusions as to the specificity of the findings for the speech disorder DAS. However, the results do provide information about DAS. The patterns can be interpreted as a problem in the automation of speech production. The results of this study strongly suggest that speech production of children with DAS is not only delayed but also deviant. These hypotheses will be further tested in a follow-up study 1;3 years later.

Acknowledgements

We gratefully acknowledge the Netherlands Organization for Scientific Research (NWO) for funding this project. This research was conducted while the first author was supported by a grant from the Foundation and Educational Sciences of the Organization (575-56-084) awarded to the second and third authors.

Notes

1. Note that, a similar reasoning can be made for the coarticulation patterns in other speech disorders. Since no other speech disorders are being considered in this study, we do not intend to draw strong conclusions as to the specificity of the findings for the speech disorder DAS, as compared to, for instance, phonological disorders.
2. Obviously, all children who were referred by the speech-language pathologists showed apraxic characteristics, however, only those who satisfied all criteria were included in the present study. Including only those children who can be considered as ‘clear’ cases of DAS enables us to study the nature of DAS.
3. The English and Dutch voiced stops /b/ and /d/ differ in voice-onset-time: in the Dutch voiced stops the voicing starts before the burst, in the English voiced stops the voicing and burst occur simultaneously.
4. Although in [əCV] both /ə/ and V are vowels, here, we will adress the first vowel as ‘schwa’ and the second vowel as ‘vowel’.
5. Also i/a-ratios were calculated. Overall, the value of the i/a-ratios was lower than of the i/u-ratios, as expected, but their patterns were similar. The i/a-ratios are not presented in the figures.
6. One sample *t*-tests on the F2-ratios could not be conducted, because there was only one ratio-value per child per consonant.
7. The statistical results have to be taken with some reservation, because due to the high intrasubject variability in the children with DAS the power of the statistical tests will be lower as compared to the NS children, which might lead to a smaller number of significant results.

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