CLINICAL SCIENCE

Acoustic analyses of diadochokinesis in fluent and stuttering children

Fabiola Starôbole Juste, Silmara Rondon, Fernanda Chiarion Sassi, Ana Paula Ritto, Claudia Aparecida Colalto, Claudia Regina Furquim de Andrade

Faculdade de Medicina da Universidade de São Paulo, Department of Physiotherapy, Speech-Language and Hearing Sciences and Occupational Therapy, São Paulo/SP, Brazil.

OBJECTIVES: The purpose of the study was to acoustically compare the performance of children who do and do not stutter on diadochokinesis tasks in terms of syllable duration, syllable periods, and peak intensity.

METHODS: In this case-control study, acoustical analyses were performed on 26 children who stutter and 20 aged-matched normally fluent children (both groups stratified into preschoolers and school-aged children) during a diadochokinesis task: the repetition of articulatory segments through a task testing the ability to alternate movements. Speech fluency was assessed using the Fluency Profile and the Stuttering Severity Instrument.

RESULTS: The children who stutter and those who do not did not significantly differ in terms of the acoustic patterns they produced in the diadochokinesis tasks. Significant differences were demonstrated between age groups independent of speech fluency. Overall, the preschoolers performed poorer. These results indicate that the observed differences are related to speech-motor age development and not to stuttering itself.

CONCLUSIONS: Acoustic studies demonstrate that speech segment durations are most variable, both within and between subjects, during childhood and then gradually decrease to adult levels by the age of eleven to thirteen years. One possible explanation for the results of the present study is that children who stutter presented higher coefficients of variation to exploit the motor equivalence to achieve accurate sound production (i.e., the absence of speech disruptions).

KEYWORDS: Stuttering; Child; Acoustics; Speech Motor Control; Diadochokinesis.

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E-mail: clauan@usp.br

Tel.: 55 11 3091-8406

INTRODUCTION

Speech is the final product of a complex network of linguistic, cognitive and sensorimotor processes. The latter involve the active regulation of forces of the muscular system and the vocal tract. The ability to control voluntary sequential motor speech movements (required for the positioning of articulators during the production of phonemes) also depends on the accuracy of the motor commands and on the smoothness of the transition between articulatory positions (1-5).

Although the etiology of stuttering is controversial, a widely held view is that it in part reflects a disorder in how different components of the speech-motor system are coordinated (6). This general perspective has motivated studies examining the relative timing of the movements of different structures in the fluent speech of persons who stutter (7,8).

The maximum rate of syllable production in non-linguistic, diadochokinesis (DDK) tasks has long been used in both research and clinical assessment contexts as a means of gaining insight into an individual's speech motor ability (9). DDK is also known as alternate motion rates (AMR) or sequential motor rates (SMR), both of which measure the speed necessary to stop a determined motor impulse and substitute it with its opposite (10); thus, DDK tasks are considered tests of neurological ability. According to the specific literature, DDK provides an acoustical index of motion speed and articulatory placement, reflecting both neuromotor maturation and the integration of structures involved in speech, such as the lips and tongue (11). Laryngeal function can also be assessed by analyzing the control of rapid and rhythmic movements of the vocal folds – i.e., their opening and closing (12).

Although a number of instrumental techniques can be used to investigate speech motor skills, such as imaging and movement transduction and point tracking (7,8), these methodologies are not easily applied to young children. Due to these obvious limitations, DDK rates are commonly

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used to assess the speech motor skills of children with speech and language disorders (13,14). Although the implications of rapid or slow DDK rates are still not clear, normative data on DDK rates have already been reported for children (13-15). These normative studies have generally sought to establish maximum repetition rates for DDK tasks, either in terms of the number of repetitions per second or the time required to produce a fixed number of syllable/ segment repetitions using a variety of consonant and vowel combinations.

In general, cross-sectional studies indicate a gradual increase in DDK rates with increasing age in typically developing children (12,13,16), with adult-like rates being achieved by age 9-10 or by age 15, depending upon the criteria used to indicate adult-like performance. Compared to adults, children's speech production measures demonstrate higher trial-to-trial variability, both for kinematic and acoustic analyses (8).

Although relatively few studies have examined the processes of speech motor control in children who stutter, some evidence suggests that children who stutter exhibit difficulty in the planning or programming of speech movements (17). Studies of the DDK rates of children who stutter have suggested that a large percentage of these children exhibit oral motor problems, as evidenced by their performance during motor tasks involving speech (18). On the other hand, although a few direct comparisons of DDK rates produced by children who stutter and their fluent peers have revealed no significant between-group differences (19), a more recent study demonstrated statistically significant differences between fluent and stuttering children in SMR tasks only, suggesting that fluent children were more able to quickly change the positions of articulators than were children who stutter (20). The authors argue that SMR tasks demand increased motor resources. This result is similar to those found in cases of speech apraxia involving the left hemisphere that present with deficits in motor planning or programming.

To understand neuromotor differences between stuttering and fluent children, this study sought to acoustically analyze DDK tasks in terms of syllable duration, syllable periods, and peak intensity.

MATERIALS AND METHODS

Participants in this study were all native speakers of Brazilian Portuguese and included 26 children (Group 1 – G1), 17 boys and 9 girls, who were diagnosed by two independent speech pathologists with stuttering behaviors. Participants in G1 were divided into two age groups: preschoolers (between 4.0 and 7.11 years, n = 16) and school-aged children (between 8.0 and 11.11 years, n = 10). The 26 speakers were recorded by a speech pathologist while producing spontaneous speech.

The 20 control speakers (Group 2 – G2), composed of 11 boys and 9 girls, were unpaid volunteers who reported no history of speech or hearing difficulty. G2 individuals were also divided into the same age groups as proposed for G1: preschoolers (n = 8) and school-aged children (n = 12).

This study received prior approval from the institution's Ethics Committee (CAPPesq – HCFMUSP 266/05), and informed consent was obtained from all of the participants' families.

Criteria for participation

Participants were selected for Group 1 (G1) if they fulfilled all of the following criteria: (a) a fluency profile outside of the age reference values (21), (b) a score of at least 11 points on the Stuttering Severity Instrument – 3 (22) and (c) at least 3 stuttering-like disfluencies (SLDs) per 100 syllables (23).

Participants were selected for Group 2 (G2) based on the absence of the above-mentioned criteria for the selection of speakers who stutter. As such, to be selected for G2, participants had to meet all of the following criteria: (a) a fluency profile within the age reference values, (b) a score of 10 points or less on the SSI-3 and (c) less than 3 SLDs per 100 syllables.

Apparatus

The participants were video/audio-recorded using a digital video camera, Sony DRC-SR62. All material was then transferred to the computer hard disc of a Dell Optiplex GX620. An HP200F Maxwell headset was used during the transcription of the samples to listen to the speech output, which was played over PRAAT software version 4.3.

The recordings of the DDK task were made in a sound-treated room using a special microphone (LeSon Gooseneck). The microphone-to-mouth distance was 8-10 cm at an angle of 45°. The DDK speech samples were directly gathered on the above-mentioned computer. The speech samples were recorded at a sampling rate of 44,100 Hz and with 16-bit quantization in a sound-proof room (i.e., background noise below 40 dB). While recording, the therapist first adjusted the input to an appropriate level and then monitored the output throughout the recording. The input level was kept constant throughout the recording. The recorded DDK samples were then digitalized as sound files ready to be analyzed using the PRAAT software.

Speech material

Spontaneous speech samples between 10 and 20 minutes in length were used for the assessment and analysis (22). The samples for all individuals (stuttering or not) were obtained using similar procedures. The children generated a spontaneous monologue on a topic of their choice; if a monologue was not possible, the therapist used prompts to elicit a sample. Prior to the monologue, the subjects were given topic suggestions, such as family, school, sports, friends, hobbies, films, television, etc. Children were able to speak continuously on these topics, and the topics were suitable for all ages. To determine the severity of the stuttering, a corpus containing 200 fluent syllables was analyzed. Orthographic transcriptions were carried out, and the stuttering episodes were marked. Single-word answers such as "yes" or "no" in response to prompting questions were excluded from the analysis. Overall, G1 presented speech samples ranging from 326 to 782 syllables (mean 534.77 ± 154.01), and G2 presented speech samples ranging from 210 to 298 syllables (mean 213.15 ± 15.48).

For the recordings of the DDK task, the repetition rate of articulatory segments was analyzed for a task requiring the ability to alternate movements. AMR (alternating motion rates) determines the speed and regularity of reciprocal jaw, lip, and tongue movements. This parameter also represents the articulatory accuracy and the respiratory and phonatory support. Participants were asked to repeat, without interruption, the sequence "pa-pa-pa" as fast as possible and without losing articulatory precision as soon as they heard the chronometer beep. Three sequences of 15 seconds each were collected. Only fluent productions were considered for analysis.

Speech sample transcription and analysis

To analyze the spontaneous speech and to determine the severity of the stuttering, orthographic transcriptions were carried out using the PRAAT software. The speech was transcribed by an experienced speech pathologist. Phonological transcriptions were used only in the regions of disfluency. PRAAT facilitates the transcription process by providing two mouse-operated cursors, superimposed on the waveform, to specify a given area for replay until the listener is satisfied with the transcription. Spectrograms were also displayed, which facilitated the assessment of speech features, such as the pause duration.

DDK speech samples were acoustically analyzed according to the methodology proposed by Wang et al. (9). Only the second recording was considered for this analysis. For each executable DDK sample file, the consonant-vowel (CV) syllable duration, the peak intensity within each CV syllable (voice onset plus vocalic interval) and the average period between the CV syllables were measured manually by the second author using the PRAAT software.

The CV syllable duration was measured considering the burst onset and the end of the vocalic nucleus. The peak intensity during each syllable interval was measured by selecting the appropriate PRAAT energy contour. The durations and peak intensities were then computed for all CV syllables to generate temporal and intensity parameters instantly. The average period between the CV syllables was measured between the voicing offsets of the syllables, i.e., between the negative slopes at the end of the syllables at the points crossing the threshold. Therefore, each period included the intersyllabic interval time and the syllable duration.

Reliability measures

Intra- and interjudge reliability measures were obtained to determine fluency at 2-6 months after the initial analysis. The complete conversational samples of five randomly selected children from the stuttering and non-stuttering groups (a total of 10 speech samples) were re-evaluated using the Sander Agreement Index formula (24). Intrajudge reliability ranged from .94-.97 for both the third author and the single judge (a trained speech pathologist). Interjudge reliability ranged from 0.91-0.96. All scores represent excellent levels of agreement.

About one month after the completion of the acoustic analysis, fifteen DDK trials (375 syllables) selected by a random number table were remeasured by the second and third authors, both of whom have experience in acoustic analysis. The peak intensity numbers between the two measures were identical in terms of both intra- and inter-examiner agreement. The Pearson correlation coefficient for the CV durations between the two measures was 0.967 and 0.912 for the intra- and inter-examiner agreement, respectively.

Statistics

SPSS 17 was used for the statistical analyses. The Kolmogorov-Smirnov test indicated that the data were not normally distributed. For this reason, the non-parametric Mann-Whitney U test was used for within- and between-group comparisons ($p<0.05$).

RESULTS

Overall, a corpus of 1,470 syllables (DDK trials) was available for observation and analysis. The data summarized in Table 1 describe the individuals' ages, the total number of stuttering-like disfluencies (SLDs), the percentage of stuttered syllables (%ss) and the total number of syllables produced in the DDK trial. Within-group comparisons indicated the following: for G1, no significant differences were observed between preschoolers and school-aged children when considering the number of SLDs (U = 66,000; $p=0.447$) and the %ss (U = 66,000; $p=0.447$). However, a highly significant difference was observed in the number of syllables produced per DDK trial (U = 28,000; $p=0.006$); school-aged children produced a higher number of syllables. For G2, significant differences were observed between preschoolers and school-aged children when considering the %ss (U = 23,000; $p=0.041$) and number of SLDs (U = 23,000; $p=0.041$); preschoolers presented a higher number of stuttered syllables and a higher number of speech disruptions. A highly significant difference was also observed for the number of syllables per DDK trial (U = 13,500; $p=0.008$); school-aged children produced a higher number of syllables.

As expected, individuals in the G1 demonstrated more stuttering behaviors than did those in the G2 group (preschoolers: U = 0.000; $p<0.001$; school-aged children: U = 0.000; $p<0.001$). Regarding the number of syllables produced on the DDK trial, no significant differences were found between G1 and G2 (preschoolers: U = 59,500; $p=0.782$; school-aged children: U = 50,500; $p=0.529$).

Table 2 shows the descriptive analyses (mean and standard deviation values) for the acoustic parameters investigated. Tables 3, 4, and 5 present the between-group comparisons. Although the groups had similar mean values, G1 demonstrated larger standard deviations for all acoustic parameters (i.e., the CV syllable duration, the average

Table 1 - Mean (standard deviation) age and speech fluency results.

	G1 Mean (SD)		G2 Mean (SD)	
	Preschoolers	School-aged children	Preschoolers	School-aged children
Age	5.63 (1.15)	9.70 (1.49)	5.87 (1.25)	9.50 (3.17)
SLDs	10.94 (6.35)	10.90 (9.21)	1.87 (1.13)	0.75 (1.21)
%ss	5.47 (3.17)	5.45 (4.60)	0.94 (0.56)	0.38 (0.61)
Syllables DDK trial	27.31 (8.03)	37.00 (6.86)	29.00 (5.78)	35.92 (4.74)

Legend: G1 – group 1; G2 – group 2; SD – standard deviation; SLDs – stuttering-like disfluencies; %ss – percentage of stuttered syllables.

Table 2 - Mean (standard deviation) values of acoustic variables.

	G1 Mean (SD)		G2 Mean (SD)	
	Preschoolers	**School-aged children**	**Preschoolers**	**School-aged children**
Syllable duration (s)	0.14 (0.04)	0.11 (0.02)	0.16 (0.02)	0.13 (0.01)
Average period of CV syllables (s)	0.27 (0.10)	0.20 (0.03)	0.26 (0.04)	0.21 (0.02)
Peak intensity (dB)	72.01 (12.34)	72.68 (13.40)	74.85 (10.52)	69.50 (9.26)

Legend: G1 – group 1; G2 – group 2; SD – standard deviation; s – seconds; CV – consonant-vowel; dB - decibel.

period of CV syllables and the peak intensity within each CV syllable). Statistical between-group analyses indicated no significant differences for any of the investigated acoustic parameters (CV syllable duration – $p = 0.115$; average period of CV syllables – $p = 0.590$; peak intensity within each CV syllable – $p = 0.773$).

When looking at the different age groups, G1 and G2 presented significant differences in the performance of preschoolers and school-aged children for the variables of CV syllable duration and average period of CV syllables. In both cases, preschoolers presented higher durations for the performed measurements.

DISCUSSION

DDK assessment in children has been used to better understand the development of speech-motor abilities (14,25). As DDK testing is easily performed by subjects with speech disorders of different severity levels, some authors believe that it has clinical value for the assessment of neuromotor speech disorders (10). A recent study in children from 9 to 12 years of age indicated that stuttering children have reduced gray matter volume in speech regions – the left inferior frontal gyrus and bilateral temporal regions – and reduced fractional anisotropy in the left white matter tracts underlying the motor regions supplying the face and larynx (26). Our study is of a different nature (clinical), and our findings concur with those of a neuroimaging study – i.e., no significant differences were observed between children who do or do not stutter in terms of the acoustic patterns produced during the DDK tasks. Our results suggest that the DDK analyses adopted in the present study seem not to have been sensitive enough to capture these potential anatomical differences between children who do stutter and those who do not.

Highly significant differences were demonstrated between children of different ages independent of the degree of speech fluency. Overall, preschoolers performed poorer. These results indicate that the observed differences are related to speech-motor development and not to stuttering itself.

Regarding the results of the number of syllables produced per DDK trial, the literature suggests that DDK rates are probably related to dimensions of the overall speech performance (9). Although a few studies have indicated that the DDK rate tends to correlate significantly with the speaking rate (14,27), others have argued that the DDK rate is more sensitive than the speaking rate or the articulation rate for the detection of abnormal articulation (28).

The present study performed extended quantitative analyses of DDK. Acoustic studies suggest that variations in peak intensity during the syllable interval may indicate difficulties with respiratory control, whereas the variation in the peak intensity during intersyllable pauses is likely to reflect continuous voicing (periodic energy) or poor articulatory control (aperiodic energy appearing as spirantization) (9). Other authors have argued that temporal parameters of the acoustic analysis for DDK, such as lengthened intersyllable pauses or a prolonged syllable duration, contribute to the slow DDK rates (29). Although our study found no significant differences between the groups, children who stuttered had greater standard deviations for all of the acoustic parameters assessed, which indicates increased performance variability. Performance variability is a hallmark of the early learning process for any complex motor skill. Variability has also been characterized as the result of an important adaptive mechanism, granting developing organisms the flexibility to modify adaptive strategies as they cope with internal and external changes (30).

Acoustic studies reveal speech segment durations and voice onset times to be the most variable measurements, both within and between subjects between the ages of two and six years; these values gradually decrease to adult levels by the age of eleven to thirteen years (31,32). Kinematic studies of speech production generally suggest that as children get older, the timing, velocity, amplitude, and patterning of their speech movements become less variable (8,17,33). A possible explanation for the results of the present study, i.e., stuttering children had more variable results than did their fluent peers, is related to the fact that only perceptually fluent productions were used for analyses. In this case, children who stutter

Table 3 - Comparisons by age group for the CV syllable duration.

		U	*p*-value
G1	Preschoolers School-aged children	39.500	0.033*
G2	Preschoolers School-aged children	21.500	0.041*

Legend: G1 – group 1; G2 – group 2; SD – standard deviation;
* - significant results

Table 4 - Comparisons by age group of the average period of CV syllables.

		U	*p*-value
G1	Preschoolers School-aged children	32.000	0.011**
G2	Preschoolers School-aged children	14.000	0.009**

Legend: G1 – group 1; G2 – group 2; SD – standard deviation; ** - highly significant results.

Table 5 - Comparisons by age group of the peak intensity within each CV syllable.

		U	*p*-value
G1	Preschoolers School-aged children	77.000	0.874
G2	Preschoolers School-aged children	34.000	0.280

Legend: G1 – group 1; G2 – group 2; SD – standard deviation; CV – consonant-vowel.

presented with higher coefficients of variations to exploit motor equivalence to achieve accurate sound production (i.e., the absence of speech disruptions). With regard to acoustic parameters, the differences between stutterers and non-stutterers tend to become more significant during adulthood, when the individual achieves full oral-motor development (34-36).

Although normally developing children have acquired most of the Portuguese sound system by the age of 5 years, with complete mastery by the age of 7 (21), truly adult-like speech-motor control may require a more protracted course of development, at least for some components of the system (37). The same explanation is valid for the decrease in SLDs observed in the speech of children in the control group (G2). During language acquisition and development, periods of speech fluency fluctuations are very common. These fluctuations are derived from linguistic uncertainties that are specially related to language morphology and syntax (38). With the development of language abilities and the maturation of the neuromotor system, these uncertainties tend to disappear. When considering children with persistent stuttering, the hallmark of this speech pathology is that speech disruptions continue to persist even as linguistic and motor abilities develop and improve.

There is clearly a need for future research concerning the abilities of stuttering individuals to perform well on DDK tasks, especially for children. For instance, future studies should follow children with stuttering to investigate the differences between those who spontaneously recovery and those who develop more persistent forms of the disorder. Other analyses can be applied to DDK tasks. For example, analyses of the types of errors made (e.g., articulatory errors, CV position errors) may possibly provide insight into the differences between speech-motor development and speech processing in stuttering and fluent individuals.

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AUTHOR CONTRIBUTIONS

Juste FS contributed to the manuscript writing and provided substantial scientific contribution. Rondon S contributed to data collection and analyses. Sassi FC organized and conducted the statistical analyses, interpretation of the results and wrote the majority of the manuscript. Ritto AP and Colalto CA participated in the data collection and analyses. Andrade CR contributed to the research and experimental design and received the research funding.

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