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Interarticulatory Coordination of the Lips and Jaw in Childhood Apraxia of Speech

Aviva Moss, M.S. and **Maria I. Grigos, Ph.D.**
Department of Communicative Sciences and Disorders, New York University, New York, NY

Abstract

Childhood apraxia of speech (CAS) is often characterized by an ability to produce phonemes in isolation, but not in more complex phonetic sequences. This has led to the hypothesis that articulator coordination is impaired in CAS, This study explored whether coordination between the lips and jaw during speech production is impaired in this group. We used two methods to investigate interarticulatory relationships. Cross-correlation analysis directly measures spatial-temporal coupling of articulator movements. The spatiotemporal index (STI; Smith, Goffman, Zelaznik, Ying, & MeGillem, 1995) measures repetition stability and has also been used as an indirect measure of interarticulatory coordination by providing an index of the coordinative consistency of the relationship between articulators within a pair (Smith & Zelaznik, 2004). Three groups of children were included: children with CAS; children with a speech sound disorder involving articulation, phonological errors, or both (the SD group); and typically developing (TD) children. A facial motion capture system was used to track upper lip, lower lip, and jaw movement during a naming task in which stimuli varied by word length. The CAS, SD, and TD children did not significantly differ in spatial–temporal coupling; however, coefficients of variation of the spatial and temporal coupling measures did differentiate the CAS and SD groups. Additionally, the CAS children were distinguished from the SD children by higher lip aperture STI values, indicating that the CAS group had more difficulty generating stable movement plans.

Keywords

apraxia of speech; speech motor coordination; speech disorder; speech production measurement

INTRODUCTION

Hallmarks of childhood apraxia of speech (CAS), which are critical for differential diagnosis, include inconsistent errors, unusual prosody, and impaired coarticulation (American Speech-Language-Hearing Association, 2007). These characteristics suggest that CAS may involve a deficit in spatial and temporal planning that may alter interarticulatory coordination. A deficit in speech motor control has been proposed by recent investigations of articulator movement in CAS. Grigos and Kolenda (2010) used facial tracking to examine

Address Correspondence to Aviva Moss, M.S., New York University, 665 Broadway, Suite 900, New York, New York 10012, PHONE: 917.309.7617, FAX: 212.995,4366, aviva.moss@nyu.edu.

changes in jaw movement in a child with CAS during production of single-syllable words across an 8-month period in which phonemic accuracy was judged to improve perceptually. Improvements in phonemic accuracy were accompanied by a decrease in jaw movement variability and an increase in jaw speed and displacement. Terband, Maassen, Van Lieshout, and Nijland (2011) studied tongue, lip, and jaw coordination in children with CAS, children with a phonological speech sound disorder and typically developing (TD) children during a reiterative speech task using electromagnetic midsagittal articulography. Children with CAS had higher variability associated with the tongue-tip–jaw relationship than control participants. No significant group differences were found in the jaw–lower lip pair or between children with CAS and the group of phonologically impaired children in either pair, indicating that during word repetition, coordinative consistency may not differentiate these groups.

Interarticulatory coordination can be conceptualized and measured in several ways. In one method, the spatiotemporal index (STI; Smith et al., 1995), which was used by Terband et al. (2011), trial-to-trial consistency of the relationship between articulators was measured. Smith and Zelaznik (2004) suggested that some interarticulator relationships represent coordinative synergies, A coordinative synergy implies that although the individual movements of effectors may vary, the functional linkage between them maintains the primary movement goal. The lip aperture synergy is considered a higher order synergy because across development, coordinative consistency is higher in this pair than other articulator pairs, reflecting a more tightly controlled relationship. The lower–lip jaw relationship is considered a lower order synergy because across development, its variability is higher than seen in lip aperture. A disadvantage of the STI is that it does not address the degree to which temporal control may impact spatial coordination. Cross-correlation, another method used to examine coordination, examines spatial and temporal coupling of the movements of two articulators to isolate aspects of coordination that may be impacted separately.

The purpose of the current study was to explore whether articulator coordination is impaired in children with CAS compared with TD children and children with a speech sound disorder characterized by articulation, phonological errors, or both (the SD group). The influence of word length on movement coordination was also examined. We explored articulator coordination from both methodologic perspectives. It was hypothesized that the CAS group would show reduced spatial–temporal coupling and have lower consistency in lip aperture and lower lip–jaw relationships than the TD and SD groups. Furthermore, the hypothesis that word length would impact the CAS group to a greater extent than the TD or SD groups was also studied. Underlying coordination deficits may be indicative of disordered speech motor control in CAS.

METHOD

The participants were three age-matched groups of children, CAS, SD, and TD (n = 6 per group), between the ages of 3 and 7 years (CAS: mean = 4.96, standard deviation = 1.37; SD: mean = 5.00; standard deviation = 1.70; TD: mean = 5.03, standard deviation = 1.50). An internal review board proposal was approved through the University Committee on

Activities Involving Human Subjects at New York University. All children completed standardized testing of language, cognition, speech production, and oral motor skills, including the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999), the Goldman-Fristoe Test of Articulation (GFTA-2; Goldman & Fristoe, 2000), Test of Early Language Development-3 (TELD-3; Hresko, Reid, & Hammill, 1999), and Columbia Mental Maturity Scale (CMMS; Burgmeister, Blum, & Lorge, 1972). A 100-word speech sample was also elicited during play. Normal hearing and average performance on the CMMS and the Receptive subtest of the TELD-3 were required for participation. Children were diagnosed with CAS if they had prosodic errors, inconsistent vowel and consonant errors, and difficulty using sounds produced in isolation in sequences. Other indicators of CAS included metathesis; articulatory groping; reduced phonetic inventory; and excessive distortions, omissions, substitutions, and additions.

A motion capture system (Vicon 460, Vicon Motion Systems, 2001) was used to track articulator movement in three dimensions at a sampling rate of 120 frames per second. Three-millimeter reflective markers were placed on the upper lip, lower lip, corners of mouth, right jaw, left jaw, and middle jaw. The right jaw marker was used to track jaw movement. Markers on the right, left, and middle forehead, nasion, and nose were used as reference markers to account for head rotation. During motion tracking, productions of one-, two-, and three-syllable words were elicited. Participants were introduced to three characters in a short story, “Pop,” “Puppet,” and “Puppypop,” represented by two-dimensional picture probes. All three characters’ names were considered real words, learned for story retell purposes. Children used one of the target words to complete a cloze sentence or respond to a “who” question cued by the picture probe. Stimuli consisted of labial sounds in order to obtain visualization of consonant production. Each stimulus was presented between 10 and 15 times in a randomized order. Only correct productions were included for analysis because underlying speech motor deficits can manifest during accurate as well as inaccurate productions (Smith, Sadagopan, Walsh, & Weber-Fox, 2010). Transcription analysis of the trials was completed. A novel listener experienced in transcription also listened to and transcribed 20% of the items. This listener did not know the probes and did not have any background information about the study. Interrater reliability calculated between the original judge and the novel listener was 85%. When items that were both considered incorrect but transcribed differently or when differences occurred on only the final consonant, which was not analyzed kinematically, were not included in reliability estimates, interrater reliability with a novel listener rose to 91%.

Kinematic data were processed using MATLAB, version 7.5 (Math Works, 2007). Cross-correlation analyses were performed using a MATLAB algorithm for three articulator pairs, jaw–lower lip (J–LL), jaw–upper lip (J–UL), and upper lip–lower lip (UL–LL). To obtain the measure of spatial coupling, the absolute value of the peak correlation coefficient (PC) was obtained for each trial. A high PC reflects a high degree of interarticulatory coupling. Each cross-correlation was converted to a z-score using a Fisher transformation to allow for computing individual and group means. All statistical analyses were completed using the associated z-scores. The measure of temporal coupling, the absolute value of the lag (Lag), was obtained using a MATLAB algorithm for each articulator pair. The Lag refers to the time required to achieve peak spatial coupling. Absolute values for both measures were used because magnitude rather than direction of interarticulator relationships was of interest. The coefficients of variation of each measure were analyzed independently. The STI for lip aperture (LASTI) and lower lip–jaw (LJSTI) was calculated using segmented displacement traces normalized for time and amplitude. The standard deviation of the traces was computed at 2% intervals across repeated productions. The STI value refers to the sum of the resulting 50 standard deviations (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). Repeated measures analyses of variance (ANOVAs) were performed for each dependent variable. Group was used as the between-subjects factor and length as the within-subjects factor. The Sidak adjustment was used to account for multiple comparisons within each ANOVA.

RESULTS

Data Corpus

A total of 540 trials were collected, of which 386 utterances were used for analysis (CAS = 126; SD = 138; TD = 122). The number of trials included for each word (i.e., *pop*, *puppet*, *puppypop*) varied by group (CAS = 61, 30, 35; SD = 55, 40, 43; TD = 44, 41, 37). Results of the analysis of effects of word length on spatial-temporal coupling are summarized in Table 1.

Spatial-Temporal Coupling

No main effect of group or interaction effect on spatial coupling was observed. A main effect of length was found such that, for the J–LL pair, spatial coupling decreased as length increased from one to two syllables, and for the J–UL and UL–LL pair, spatial coupling decreased with three syllables. For the J–LL pair, a main effect of length was found ($F[2,15] = 26.18$; $P < .0001$). For this pair, spatial coupling significantly decreased from *pop* to *puppet* ($P < .0001$; d = 1.62) and from *pop* to *puppypop* ($P < .0001$; d = 1.39). A main effect of length was also found for the J–UL pair ($F[2,15] = 4.87$; $P = .02$), but no effect of group or interaction was found. For this pair, productions of *pop* were significantly more tightly coupled than *puppypop* ($P = .03$; d = .83). For the UL–LL pair, there was also a main effect of length ($F[2,15] = 9.629$; $P = .001$), Spatial coupling decreased from *pop* to *puppypop* ($P = .001$; d = 1.0) and from *puppet* to *puppypop* ($P = .004$; d = .92). There was no effect of group or interaction on temporal coupling for all pairs. For the J–LL pair, there was a main effect of length ($F[2,15] = 3.75$; $P = .04$). The Sidak method found no significant pairwise comparisons. Because there was a main effect of length, *t*-tests were performed to explore the impact of length further. *t*-Tests revealed that productions *of puppet* were significantly less synchronous than *puppypop* ($t = 2.65$; $P = .02$; d = .74). For the J–UL pair, there was a main effect of length ($F[2,15] = 12.41$; $P < .0001$). Lags were significantly shorter for *puppypop* than *pop* ($P = .001$; d = 1.36) or *puppet* ($P = .007$; d = .87). For the UL–LL pair, there was no statistically significant effect of length.

The coefficient of variation of the PC (PCcov) revealed a main effect of group for the J–LL pair ($F[2, 15] = 4.96$; $P = .022$). The CAS group had significantly higher average PCcov across utterances than the SD group ($P = .028$). No significant effects were found in the other articulator pairs. A main effect of group was found on the coefficient of variation of the lag (Lcov) (F[2,15] = 4.27; *P* = .03) for the J–LL pair. The Sidak adjustment found no significant pairwise comparisons. Results of *t*-tests indicated that the CAS group had higher Lcov than the SD group (*P* = .03) and the TD group had significantly higher Lcov than the SD group (*P* = .02). A main effect of length (F[2,15] = 10.22; *P* < .0001) and group (F[2,15] = 4.37; *P* = .03) was found for the J–UL pair. Lcov was higher in the CAS group relative to the SD group (*P* < .05), and the Lcov for *pop* and *puppet* was significantly different from Lcov for *puppypop* (*P* = .006 and = .003, respectively). Although no interaction was found, Lcov appeared to decrease in the CAS and SD groups and increase in the TD group as length increased. No statistically significant effects were found in the UL–LL pair. Table 2 summarizes the effects of syllable length on the coefficient of variation.

Coordinative Consistency

LASTI and LJSTI were used to measure the consistency of intereffector relationships. Figure 1 demonstrates the significant effect of group on LASTI (F[2,15] = 4.87; *P* = .02). LASTI was significantly higher in the CAS group than in the SD group (*P* = .02). Although the Group × Length interaction was not significant, the CAS group demonstrated much larger effect sizes between *pop* versus *puppet* and *pop* versus *puppypop* (d = 1.79, d = .77) compared with the SD group (d =.89, d =.09) and TD group (d = .18, d = .22). Although there was no effect of length or group on LJSTI, there was a significant Group × Length interaction effect (F[2,15] = 3.48; *P* = .02) as seen in Figure 2. Consistency decreased in the CAS group with length. It increased or stayed the same across utterances in the TD and SD groups.

DISCUSSION

The purpose of the current study was to investigate articulator movement coordination in children with CAS relative to their TD and SD peers. Although it was hypothesized that CAS involves a deficit in spatial–temporal coupling, no group differences were found in the PC and Lag measures calculated between articulator pairs. The absence of a group effect in both of these measures may have been caused by a lack of statistical power or to the possibility that these measures are not sensitive enough to detect group differences. We are encouraged that differential effects of length were observed, suggesting that these measures are sensitive to differences in planning or programming demands. Children with CAS achieved a magnitude of spatial–temporal control comparable to their peers, sufficient for producing words accurately. Word length affected production similarly across groups. Because word length was associated with increased temporal coupling in J–LL and J–UL, we speculate that children may use temporal control as a compensatory strategy to achieve accurate production as spatial demands increase.

Group differences emerged in the variability of spatial–temporal coupling, measured by PCcov and Lcov. In the J–LL pair, children with CAS were more variable in their degree of spatial coupling (PCcov) compared with the SD children. Similarly, in both the J–LL and J–UL pairs, temporal coupling (Lcov) was more variable in the CAS than in SD groups. There was a trend for variability to be similar between the TD and CAS groups. These findings indicate that children with SD have fewer movement options available to them to achieve accurate speech. Greater variability in children with CAS suggests that reducing variability may be an implicit strategy available to only some children with speech production difficulties. If speech production, is demanding, maintaining variability comparable to TD children may lead to errors for children with CAS. The LASTI also differentiated the CAS from SD groups, further demonstrating that CAS is characterized by inconsistency in how lip aperture is achieved and suggesting that children with CAS had more difficulty generating a stable movement pattern. We suspected that as length increased, children with CAS would have more difficulty than their peers in achieving spatial–temporal coupling and movement stability. This hypothesis was supported by the interaction in the LJSTI.

CONCLUSIONS

This study provides evidence that aspects of coordination may differentiate children with CAS from those with articulation or phonological impairments. Specifically, variability in individual articulator movements and in the overall consistency of the movement goal appears to differ in these groups. Examining inaccurate productions in the future will provide a more comprehensive understanding of coordination differences in these groups.

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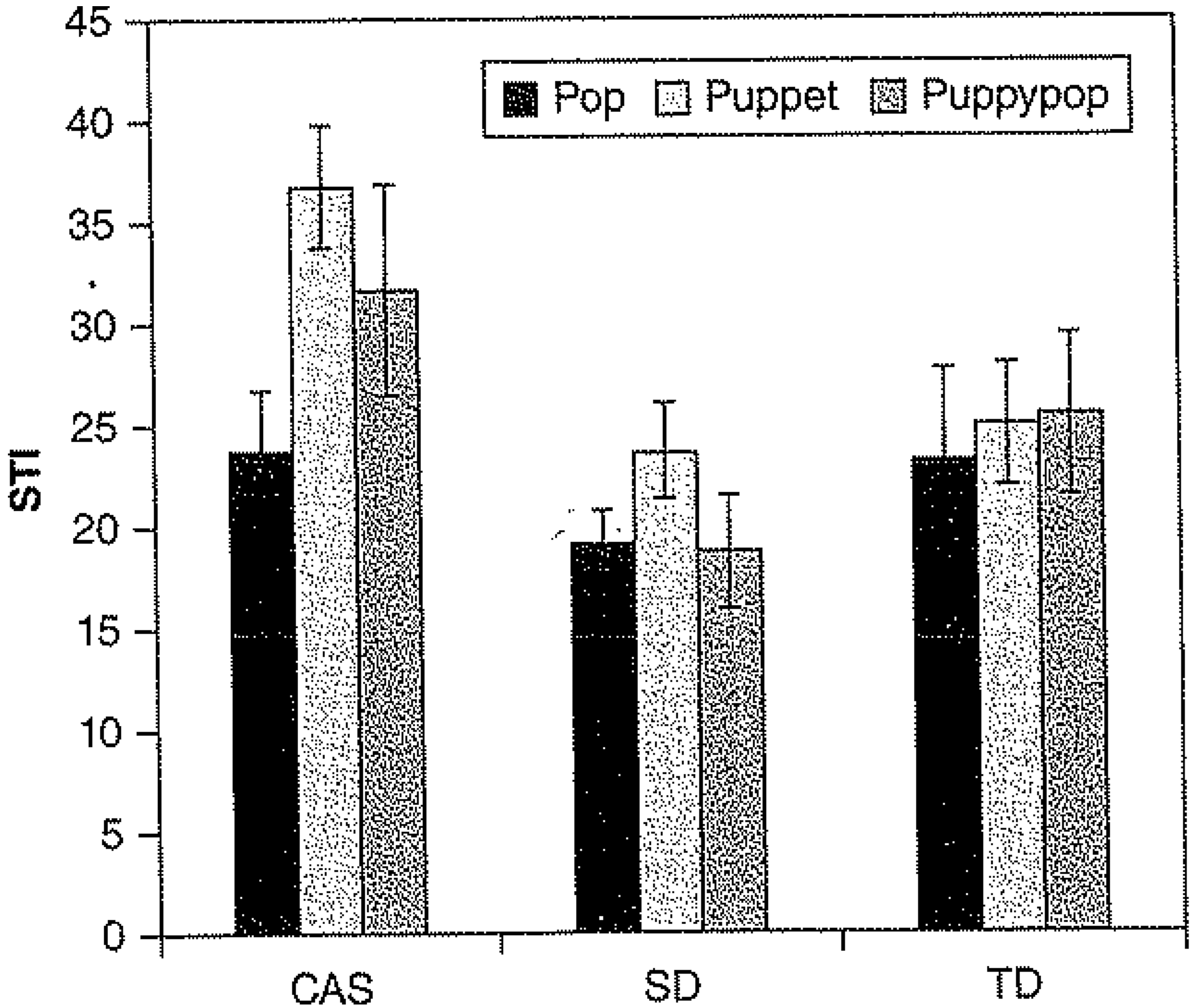

Figure 1.
Mean lip aperture spatiotemporal index (STI) in pop, puppet, and puppypop. CAS = childhood apraxia of speech; SD = speech disorder; TD = typically developing.

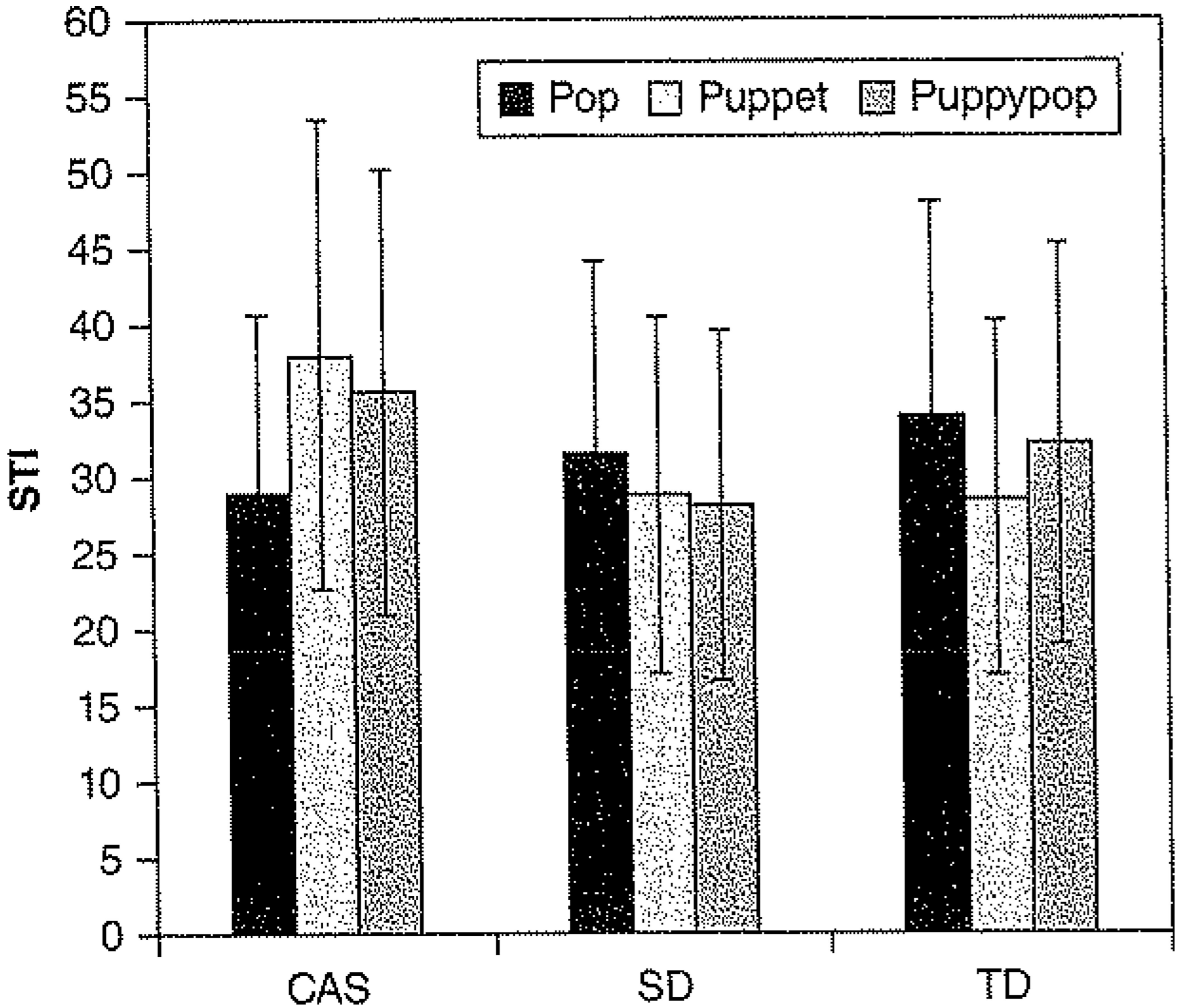

Figure 2.
Mean lower lip–jaw spatiotemporal index (STI) (LJSTI) in pop, puppet, and puppypop. CAS = childhood apraxia of speech; SD = speech disorder; TD = typically developing.

TABLE 1

Mean Correlation, Coefficient and Lag for Each Articulator Pair and Probe

	Mean PC *r* (SEM *z*)			Mean Lag (SEM, msec)		
	Pop	**Puppet**	**Puppypop**	**Pop**	**Puppet**	**Puppypop**
J–LL	*†			‡		
CAS	0.90 (.18)	0.7 (.03)	0.68 (.11)	24.33 (2.78)	28.54 (2.8)	21.67 (2.2)
SD	0.87 (.15)	0.66 (.10)	0.76 (.10)	25.48 (3.25)	25.15 (4.48)	17.03 (3.43)
TD	0.82 (.12)	0.7 (.07)	0.62 (.13)	20.5 (3.5)	20.5 (1.67)	18.87 (2.77)
J–UL	†			†‡		
CAS	0.67 (.04)	0.59 (.08)	0.57 (.11)	35.15 (2.25)	34.06 (2.64)	25.6 (2.71)
SD	0.58 (.07)	0.53 (.07)	0.54 (.07)	38.43 (1.65)	35.92 (2.97)	29.83 (2.77)
TD	0.66 (.11)	0.5 (.05)	0.46 (.08)	34,29 (2.33)	31.69 (3.53)	27.86 (3.04)
UL–LL	†‡					
CAS	0.72 (.14)	0.67 (.11)	0.55 (.08)	25.98 (4.24)	22,41 (4.23)	23.98 (6.05)
SD	0.65 (.09)	0.7 (.10)	0.6 (.09)	26.87 (1.95)	21.61 (4.13)	25.83 (3.85)
TD	0.71 (.10)	0.68 (.10)	0.53 (.06)	23.67 (4.05)	25.56 (2.55)	26.78 (1.38)

[*] Significant length effect between *pop* and *puppet* ($P < .0001$).

[†] Significant length effect between *pop* and *puppypop* ($P < .035$).

[‡] Significant length effect between *puppet* and *puppypop* ($P < .025$).

CAS = Childhood Apraxia of Speech; SD = speech disordered; TD = typically developing; J–LL = jaw–lower lip; J–UL = jaw–upper lip; UL–LL = upper lip–lower lip; SEM = standard error of the mean.

TABLE 2

Mean Coefficient of Variation of the Correlation Coefficient and the Lag for Each Articulator Pair and Probe*

	Mean PCcov (SEM)			Mean Lcov (SEM)		
	Pop	Puppet	Puppypop	Pop	Puppet	Puppypop
J–LL						
CAS	**0,33 (.13)**	**0.54 (.22)**	**0.54 (.22)**	**0.51 (.21)**	**0.48 (.20)**	**0.73 (.30)**
SD	**0.23 (.09)**	**0.21 (.08)**	**0.25 (.10)**	**0.31 (.13)**	**0.23 (.09)**	**0.35 (.14)**
TD	0.46 (.19)	0.44 (.18)	0.36 (.15)	0.55 (.23)	0.57 (.23)	0.65 (.27)
J–UL				†‡		
CAS	0.52 (.21)	0.51 (.21)	0.43 (.17)	**0.52 (.21)**	**0.51 (.21)**	**0.43 (.17)**
SD	0.41 (.17)	0.33 (.14)	0.31 (.12)	**0.17 (.07)**	**0.05 (.02)**	**0.31 (.15)**
TD	0.48 (.20)	0.58 (.23)	0.64 (.26)	0.28 (.17)	0.37 (.13)	0.56 (.23)
UL–LL						
CAS	0.74 (.30)	0.54 (.22)	0.45 (.19)	0.67 (.28)	0.73 (.30)	0.3 (.12)
SD	0.35 (.14)	0.33 (.14)	0.39 (.16)	0.35 (.14)	0.4 (16)	0.4 (.16)
TD	0.5 (.20)	0.55 (.22)	0.45 (.18)	0.73 (.3)	0.57 (.23)	0.54 (.22)

[*] Significant group differences relative to CAS are represented in bold ($P < .05$).

[†] Significant length effect between *pop* and *puppypop* ($P < .007$).

[‡] Significant length effect between *puppet* and *puppypop* ($P < .004$).

CAS = Childhood Apraxia of Speech; SD = speech disordered; TD = typically developing; Lcov = coefficient of variation of the lag; PCcov = coefficient of variation of the peak correlation coefficient; J–LL = jaw–lower lip; J–UL = jaw–upper lip; UL–LL = upper lip–lower lip; SEM = standard error of the mean.