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Interarticulator coordination in children with and without cerebral palsy

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Abstract

The current study investigates how interarticulator coordination changes across speaking tasks varying in articulatory and linguistic demands for children with CP and their typically-developing peers. Articulatory movements from 12 children with spastic CP (7M, 5F, 4–15 years of age) and 12 typically-developing age- and sex-matched peers were cross-correlated to determine the degree of spatial and temporal coupling between the upper lip and jaw, lower lip and jaw, and upper and lower lips. Spatial and temporal coupling were also correlated with intelligibility. Results indicated that children with CP have reduced spatial coupling between the upper and lower lips and reduced temporal coupling between all articulators as compared to their typically-developing peers. For all participants, sentences were produced with the greatest degree of interarticulator coordination when compared to the diadochokinetic and syllable repetition tasks. Measures of interarticulator coordination were correlated with intelligibility for the speakers with CP.

Keywords

Cerebral palsy; dysarthria; intelligibility; speech motor control

Speech impairments in children with CP

Cerebral palsy (CP) is a group of non-progressive disorders caused by injury to the fetal or neonatal nervous system [1, 2]. The disorders are characterized by chronic disturbances of movement and impairments in the sensory, cognitive, and communication domains [1, 2]. As many as 20% [3] to 42% [4] of children with CP have speech and/or language impairments, including dysarthria [4–6].

Speakers with dysarthria secondary to CP may have reduced intelligibility, or an overall decreased ability to be understood by listeners [7–10], reduced speaking rates [5, 11], due to reduced pitch ranges [12], prolonged syllable durations [9], and reduced vowel areas [5, 13]. However, subtle speech deficits can also be observed in children with CP who are judged not to have dysarthria. For example, some children with CP are generally rated as intelligible in

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most situations but they demonstrate reduced intelligibility when producing speech tasks with greater articulatory and linguistic complexity (e.g., longer sentences; [8]).

Impairments of the speech mechanism may account for the dysarthric characteristics reported in this population. Speakers with CP demonstrate increased segmental durations for consonants and vowels [14]. In addition, speakers with CP consistently produce greater lip and jaw displacements during oral movements than their typically-developing peers during the production of syllables [11, 15], words [16, 17], diadochokinetic tasks [11] and sentences [11]. This increase in oral displacement suggests that children with CP may have a reduced ability to grade force control, creating more ballistic movements during speech and slowed speaking rates [11]. Reductions in force control have also been observed in other motor systems of children with CP. Decreased force control has been postulated as the reason for impairments in reaching [18] and in speech breathing [19]. Alternately, the increase in oral displacements may be used as a strategy to increase proprioceptive feedback, particularly of the jaw, which may be used to stabilize speech movements and movement coordination [20].

Reduced coordination of movements of the speech mechanism may underlie the dysarthric speech characteristics in this population. The respiratory and laryngeal subsystems are not well coordinated, negatively impacting vocal quality and loudness [7, 19] and coordination of movements may negatively impact the speech development of children with motor impairments [21]. Many children with dysarthria secondary to CP also have a slow speaking rate [5, 11], which requires the coordination of multiple speech subsystems and articulators, including respiratory, laryngeal and oral articulatory movements. Similarly, the overall reduction in speech intelligibility observed in this group of children may be negatively affected by speech movement impairments and reduced coordination among articulators [22, 23]. Reductions in oral motor control have been shown to be associated with speech intelligibility in children with speech sound disorders [24], however it is not known if this association between speech motor control and intelligibility exists in children with dysarthria.

Task demands

Like many complex motor behaviors, speech arises from the interaction of multiple domains including speech motor control, language and cognition [25, 26]. These domains have been shown to affect speech production in typically-developing children [27, 28]. For example, when producing movements for tasks requiring linguistic and articulatory specification (e.g., words) toddlers move their lips and jaw with greater speeds and larger oral excursions as compared to movements with no articulatory specification [27]. From preschool years onward, speakers predictably change articulatory strategies, such as increasing or decreasing oral opening, for different tasks. Speaking tasks that require greater hyper-articulation so that content is conveyed to a listener, such as narrative retells, are produced with faster movement speeds and slower speaking rates because oral excursions are increased [29]. In contrast, tasks with increased articulatory demands and little linguistic content (e.g., diadochokinetic task, such as saying “ba” quickly and repeatedly) are produced with hypo-articulation or smaller oral excursions, resulting in slower movement speeds but faster speaking rates [29]. Similar task effects have been observed in individuals with CP. Individuals with CP also consistently increased oral excursions when producing tasks requiring greater linguistic demands (e.g., sentences) and decreased their oral excursions for tasks with greater articulatory demands (diadochokinesis, or DDK), similar to their typically-developing peers; however their speaking rates were lower than their typically-developing peers [11]. In addition, intelligibility in children with CP is impacted by linguistic and articulatory demands [8, 30] and the degree that intelligibility is impacted may be affected by the severity of impairment to the speech mechanism [30].

Interarticulator coordination

One relatively unexplored aspect of speech motor control in children with CP is the spatiotemporal coordination between articulators. In typical development, spatial and temporal coupling among the lips and jaw increase between the ages of 1 to 6 years, with further refinement into adulthood, and these couplings are proposed as the reason for the poor intelligibility observed at very young ages [31]. Reduced temporal coordination between the lower lip and jaw has been reported in children with CP [15]. Therefore, interarticulator coordination may be one underlying reason for reduced intelligibility in (a) children with dysarthria secondary to CP and (b) during the production of utterances that have increased articulatory and linguistic demands in children with CP but no dysarthria [8]. Similarly, other researchers have suggested that incoordination is one of the core movement disorders that impact the motor development of children with CP [1]. For example, incoordination has been linked to decreased ability to maintain balance [32] and to change postures [33]. In addition, studies have demonstrated that children with CP will co-activate agonist and antagonist muscle groups during gross motor movements rather than a more coordinated alternating pattern of activation [33]. These findings suggest that children with CP may have reduced interarticulator coordination in the oral motor system.

This reduced interarticulator coordination may affect the intra- and inter-gestural coordination needed to produce speech. In the task-dynamic model of articulatory phonology [34, 35], speech is produced through combination of gestures, typically a description of vocal tract constrictions. These gestures must be coordinated across multiple levels [35] and are affected by speaking demands [36]. Examining how coordination of the lips and jaw across speaking tasks varying in articulatory and linguistic demands differ between children with CP ranging in severity of speech impairments and their typically-developing peers will provide greater insight into how interarticulator coordination of the oral articulators may affect speech production.

Aims

The aims of the current investigation are to examine the spatial and temporal interarticulator coordination among the jaw, upper lip, and lower lip across speaking tasks varying in articulatory and linguistic demands in children with CP and their typically-developing peers. It is hypothesized that children with CP will have lower spatial and temporal coupling among these articulators than their typically-developing peers across various speaking tasks. In addition, it is also hypothesized that for both groups, spatial and temporal coupling will decrease as linguistic demands increase. To determine if interarticulator coordination may impact speech intelligibility, the current study includes children with CP ranging in severity of dysarthria. It is hypothesized that increased spatial and temporal coupling is associated with increased speech intelligibility.

Methods

Participants

The participants included 12 children with spastic CP with a range of speech impairments (no dysarthria to severe dysarthria) and 12 typically-developing age- and sex-matched (TD) peers. All participants passed a hearing screening at 0.5, 1, 2, and 4 kHz at 20 dB [37]. Participants had their language tested using the Clinical Evaluation of Language Fundamentals – Preschool 2nd edition [CELF-P2; 38] or the Clinical Evaluation of Language Fundamentals – 4 [CELF-4; 39].

Single word and sentence speech intelligibility was assessed using the Test of Children's Speech+ [TOCS+; 40] for participants younger than 10 years or with the Speech Intelligibility Test [SIT; 41] for the participants older than 10 years. One child with CP did not complete either portion of the TOCS+, so her intelligibility was assessed using an informal narrative retell procedure. Another participant with CP only completed the single word intelligibility portion of the TOCS+. Undergraduate and graduate speech, language and hearing sciences students judged the intelligibility of each participant's speech by orthographically transcribing the words and sentences heard. Each sample was independently transcribed by three different judges. Three certified speech-language pathologists with an average of 19.67 years of clinical experience judged the speech characteristics of the participants with CP. A speech sample taken from a conversation with each participant with CP was played. Each judge independently noted any of the [42, 43] Darley, Aronson, & Brown (1969) perceptual characteristics of dysarthria in each speech sample and then compared judgments with the others. These characteristics are a widely-used set of criteria for dysarthric speech and are shown to be reliable across speech-language pathologists [44]. The judgments were discussed until a consensus was reached about the perceptual characteristics present in each speech sample. Participant characteristics including GMFCS levels [45] are shown in Tables I and II.

Procedure

Participants were seated in front of an eight-camera optical motion capture system (Motion Analysis, Ltd, Santa Rosa, CA). Small, spherical reflective markers (2 mm in diameter) were placed on participants' faces. A rigid head marker, consisting of four reflective markers and a mini microphone was placed on participants' foreheads. Markers were also placed on the center of the upper lip and lower lip near the vermillion border. Three reflective markers were placed on the jaw. The first was placed on the center of the jaw and one was placed on approximately 1–2 cm on either side of the center marker. Simultaneous digital video and audio was recorded and was later used to identify the target oral opening and closing movements of the lips and jaw.

Speaking tasks

Speakers produced three tasks varying in articulatory and linguistic demands. Speaking tasks included a task intended to examine the capacity of the speech motor system (diadochokinetic or DDK "buh"), a task that had fewer articulatory demands than the DDK but had greater language formulation demands (sentence repetition, "Buy Bobby a puppy") and a task that had minimal articulatory and language formulation demands (syllable repetition, "uhba"). The DDK task required the least linguistic demands than the other tasks [29], though as a maximum performance task of the articulatory system had the greatest articulatory task demands. Participants were required to produce the syllable "buh" repeatedly as quickly and clearly as they could in a single breath. Many of the participants were able to produce many (20 or more) repetitions on that single breath group. In contrast, the syllable and sentence repetition task required the participant produce fewer syllables in total (two syllables per breath group for the syllables, six syllables per breath group for the sentences) and fewer syllables on a breath group. In addition, these tasks were produced at a comfortable, habitual speaking rate.

The sentence repetition task had the most linguistic demands on the speaker as it imposed phonological and syntactic structure and semantic meaning [29]. Finally, the syllable repetition task had the least articulatory demands (two syllables) and less linguistic demands as it only imposed a syllabic structure that conformed to the rules of English phonology.

Whenever possible, the first five tokens of the DDK were dismissed from further analysis, as repetitions after a breath are recommended to be discarded [46, 47]. The next ten tokens of the DDK task were analyzed; however some speakers with CP, specifically speakers 1, 2 and 4, had short breath groups and could not produce more than 10 repetitions in one breath. For those speakers, 10 repetitions from multiple attempts were analyzed.

Speakers were also asked to produce 10 repetitions of the syllable and sentence repetition tasks at their habitual rate and loudness. Speakers were encouraged to pause between each repetition (e.g., produce one repetition in a breath group). If the speaker produced the syllable or sentence with phonemic errors (distortions were considered acceptable) or with an unusual pause during the production of the syllable or the sentence, the speaker was asked to produce an additional repetition. Only fluent, correct productions as judged by trained research assistants were included in the final analysis.

Post-processing

Markers recorded during the session were labeled using Cortex (Motion Analysis, Ltd.). Target lip and jaw closing and opening movements were then identified using the video by trained research assistants. MATLAB [48] algorithms in SMASH [49] subtracted head movement from the rigid head marker from the jaw and lip movement traces by determining the Euclidean distance between the head marker and the jaw and lips markers. Jaw movements from either the jaw marker to the left or the right of the center marker were used to reduce flesh point tracking error [50]. All jaw and lip movement traces were parsed using the jaw signal because it is the most stable of the three articulators [31]. The jaw signal was then subtracted from the lower lip signal in order to evaluate independent lower lip movement. The target VCV sequence of /ʌbʌ/ from "b**uhbuh**" of the DDK, "**uhba**" and "B**uy Bo**bby a puppy" was analyzed as shown in Figure 1. The VCV sequence was used so that each repetition included the mouth closing an opening gesture. The beginning of the target phrase was defined as the greatest distance of the jaw from the head marker in the middle of the first vowel. The end of the target phrase was defined as the greatest distance of the jaw from the head marker in the middle of the second vowel.

To evaluate interarticulator coordination, the movement traces of the articulators, as shown in Figure 1, were cross-correlated. This approach was chosen so that measures of spatial and temporal coordination could be evaluated separately from each other. To obtain the interarticulator coordination of the jaw, lower lip (independent of the jaw), and upper lip, the movement traces of each articulator were low-pass filtered (F_{LP}=10 Hz) and then cross-correlated with the others [31]. For example, the jaw signal was cross-correlated with the lower lip, the jaw with the upper lip, and the upper lip with the lower lip. The cross-correlation function yields two variables: the cross-correlation coefficient and the lag. The correlation coefficient represents the degree of spatial coordination between the two articulators, whereas the lag represents the degree of temporal coordination between the two articulators. The function was specified to find a peak in the correlation coefficient in a 200 ms window [31]. A pair of articulators with a high degree of spatial and temporal coordination would have high correlation coefficients and low lag values. In contrast, articulators with low degree of spatial and temporal coordination would have low correlation coefficients and high lag values. To aid the interpretation of the cross-correlations, the absolute value of the correlation coefficients and the lags were calculated to determine the magnitude of spatial and temporal coordination between each pair of articulators [31].

Statistical analyses

The means for the absolute values of the cross-correlation coefficients and the lags for each articulator pair and task were Winsorized using the 25th and 75th percentile Tukey hinges to calculate the upper and lower bounds of the distribution. For each pair of articulators, multilevel models were conducted using PROC MIXED in SAS (9.4) [51] to examine the between-subjects fixed effects of Age, Group (CP, TD) and Task (DDK, syllable, sentence) and a random effect of participant on the outcome variables of the spatial (correlation coefficient) and temporal (lag) coupling. Least-square means with a Bonferroni adjustment were used to examine pair-wise comparisons for significant effects. The homogeneity of variance was tested using an *F*-test to determine if the variances between the groups were equal. When unequal variances were detected, the final multilevel model was adjusted by specifying group on the repeated statement, which accounts for unequal variances between the groups.

Finally, for each pair of articulators, the averaged absolute values of the cross-correlation coefficients and lags were calculated for each speaking task produced by a participant. These values were then correlated with word and sentence intelligibility using Pearson correlations to determine how spatial and temporal coordination relates to speech intelligibility. The averaged cross-correlation coefficient and lags for each participant are shown in Tables III and IV.

Results

Spatial coordination

The spatial coupling of the upper lip and jaw is shown in Figure 2. Higher correlation coefficients represent greater spatial coupling and lower correlation coefficients represent reduced spatial coupling. There was a significant effect of Age [$F(1, 665) = 38.13$, $p<0.001$, $\eta^2_{\text{partial}}=0.05$]. There was a significant effect of Task [$F(1, 676) = 3.90$, $p<.05$, $\eta^2_{\text{partial}}=0.01$]. The DDK task had significantly lower spatial coordination between the upper lip and jaw than the sentence task. There was no significant effect of Group or a significant Group × Task interaction. The variances between the groups were not significantly different.

Figure 3 displays the spatial coupling of the jaw and lower lip. A significant main effect of Age [$F(1, 673) = 7.44$, $p<0.01$, $\eta^2_{\text{partial}}=0.008$] was found. A significant main effect of Task [$F(2, 675) = 52.10$, $p<0.001$, $\eta^2_{\text{partial}}=0.17$] was found. The spatial coupling was highest for simple sentences as compared to syllable or DDK and that syllables had a higher degree of spatial coupling between the jaw and lower lip than DDK. There was no significant Group effect or a significant Group × Task interaction. The variances between the groups were not significantly different.

The spatial coupling of the upper and lower lips is shown in Figure 4. There was a significant effect of Age [$F(1, 673) = 33.18$, $p<0.001$, $\eta^2_{\text{partial}}=0.05$]. There was a significant Group effect [$F(1, 678) = 5.00$, $p<0.05$, $\eta^2_{\text{partial}}=0.007$]. Children with CP had reduced spatial coupling as compared to their TD peers. There was also a significant Task effect [$F(2, 677)= 11.37$, $p<0.001$, $\eta^2_{\text{partial}}=0.03$]. For both groups the DDK task had less spatial coupling of the lower and upper lips as compared to the other tasks (syllable, sentences). In addition, the spatial coupling was reduced for syllables as compared to sentences. There was no significant Group × Task interaction. The variances between the groups were not significantly different.

Temporal coordination

The temporal coupling of the upper lip and jaw is shown in Figure 5. Lower lags represent greater temporal coupling between the articulators and higher lags represent reduced temporal coupling. A significant effect of Age was found [$F(1, 590) = 25.99$, $p<0.001$, $\eta^2_{\text{partial}}=0.04$]. There was a significant interaction of Group × Task [$F(2, 617) = 10.53$, $p<0.001$, $\eta^2_{\text{partial}}=0.03$]. Post-hoc tests revealed that the TD peers had smaller lags for the syllable tasks, or greater temporal coupling, than the CP group. A significant effect of Group [$F(1, 618) = 5.14$, $p<0.05$, $\eta^2_{\text{partial}}=0.006$] was found. Children with CP had overall greater lags, or less temporal coupling, than the TD group. There was also a significant main effect of Task [$F(2, 617) = 3.34$, $p<0.05$, $\eta^2_{\text{partial}}=0.007$]. The DDK task had higher lags, or lower temporal coupling, than the sentence task. The variances between the groups were significantly different [$F(1, 614) = 14.31$, $p<0.001$].

The temporal coupling of the jaw and lower lip is displayed in Figure 6. A significant effect of Group was found [$F(1, 582) = 7.12$, $p<0.01$]. The CP group had greater lags than the TD group. A significant effect of Task was also found [$F(2, 672)= 100.22$, $p<0.001$, $\eta^2_{\text{partial}}=0.23$]. DDK had higher lags, or a lower degree of temporal coupling, than the syllables and sentences and syllables had higher lag values than sentences. There was no significant effect of Age or a significant Group × Task interaction. The variances between the groups were significantly different [$F(1, 681) = 7.99$, $p<0.01$].

Figure 7 shows the temporal coupling of the upper lip and lower lips. There was a significant effect of Age [$F(1, 505)= 15.81$, $p<0.001$, $\eta^2_{\text{partial}}=0.03$]. A significant Group × Task interaction [$F(2, 530) = 23.35$, $p<0.001$, $\eta^2_{\text{partial}}=0.06$] was found revealing that the children with CP have greater lag values, or reduced temporal coupling of the upper and lower lips, for the syllable task as compared to the TD peers. In addition, the CP group demonstrated higher lags for the DDK task as compared to the sentences, and syllables had greater lags than sentences. The TD group had higher lags for the DDK as compared to the syllable task. There were a significant main effects of Group [$F(1, 531)= 15.73$, $p<0.001$, $\eta^2_{\text{partial}}=0.02$] and Task [$F(2, 530)= 16.78$, $p<0.001$, $\eta^2_{\text{partial}}=0.04$]. There was no significant main effect of Age. The variances between the groups were significantly different [$F(1, 683) = 30.24$, $p<0.001$].

Associations among spatial and temporal coordination and intelligibility measures

To examine the strength of association between spatial and temporal interarticulator coordination and intelligibility, Pearson correlations were conducted between the cross-correlation coefficients and lags for each articulator pair and task with the intelligibility scores for each group. The correlations are listed in Tables V and VI.

Discussion

The current investigation examined how interarticulator coordination of speakers with CP with and without dysarthria compared to their age- and sex-matched typically-developing peers. Participants with CP demonstrated decreased spatial coupling between the upper and lower lips. In addition, participants with CP demonstrated reduced temporal coupling for all three pairs of articulators. In addition, there was evidence that articulatory and linguistic task demands affect spatial and temporal coupling. Finally, several significant correlations between spatial and temporal coupling and single-word and sentence intelligibility scores were found for the children with CP and a somewhat smaller number of significant correlations were found for the typically-developing peers.

Both the participants with CP and their typically-developing peers had relatively high degrees of spatial and temporal coupling among the jaw, upper lip and lower lip across all tasks. The correlation coefficients, representing the spatial coupling, ranged from 0.70 to 0.98 across all tasks for all pairs of articulators for the TD peers. This finding is slightly higher than those previously reported by Green and colleagues [31] for typically-developing six-year-olds and adults, though this difference may be due to the shorter phonetic phrase analyzed in the current study. However, the degree of temporal coupling observed in the TD group is similar to those previously reported for six-year-olds and adults [31].

Children with CP have reduced spatiotemporal coordination

The speakers with CP had reduced spatial coupling, represented by lower correlation coefficients, as compared to their typically-developing peers, for the upper lip and lower lip, particularly for the DDK task. More strikingly, children with CP had reduced temporal coupling, as represented by higher lags, than their TD peers for all three articulator pairs. This reduction in temporal coupling is similar to previous findings [15]. Because the CP group included speakers with no dysarthria, the lack oromotor involvement in these children may have diminished the group differences.

This reduction in coordination among speech structures mirrors the incoordination between speech subsystems reported in this population. For example, many individuals with CP have reduced coordination of the respiratory and laryngeal subsystems leading to dysphonic and dysarthric speech characteristics [7, 19] and slowed speaking rates, which requires the coordination of all speech subsystems [8, 11]. Similarly the reduction in spatial coupling of interarticulator coordination of the children with CP may be one reason for some of the articulatory impairments observed in this population. In studies of typically-developing children, reduced spatial and temporal coupling of articulatory movements are associated with immature speech movements [31]. The current finding of reduced interarticulator coordination in children with CP lends further support that speech development for these children is complicated by the presence of underlying neuromotor deficits [8] and reduced interarticulator coordination may be one reason for the speech intelligibility deficits seen in many of these children.

The reduced interarticulator coordination is similar to findings across other motor systems in children with CP. Children with spastic CP have reduced motor coordination, including delayed muscle activation and increased co-activation of agonist-antagonist muscle groups in gross- and fine-motor behaviors including balance [52], squatting [33], reaching [53] and grasping [54]. Neurological differences observed in children with CP may account for the coordination deficits observed in this population [55]. However, further research directly linking these neural differences with speech production and speech movements is needed.

In addition, further investigation is needed to determine if this finding represents a more protracted course of articulatory refinement for children with CP or if this reduction in coordination persists into adulthood. Similarly, examining children with CP at younger ages, particularly during speech and language acquisition will inform the developmental course of speech motor control in these children. Although older children with CP have reduced coordination, studies of infants with CP demonstrate the opposite finding. Infants with CP have reduced coordination in activities such as sitting [56] as compared to typically-developing peers. Increased coupling may be a marker of less mature movements [31] and this increased coordination in infancy may reflect impaired movements in infants with CP. In addition, increased coupling in at-risk infants are linked to coordination difficulties at later ages [57]. Potentially infants with CP may start out with a greater degree of coordination which may remain relatively static during development, whereas the coordination of their typically-developing peers continues to increase and surpass the coordination of children with CP. Research examining how interarticulator coordination in infants with CP and their typically-developing peers change longitudinally is needed to evaluate how the developmental trajectories of coordination compare between these groups of children.

It is unclear what degree of interarticulator coordination is optimal for speech production. Increased interarticulator coordination and speech movement stability is associated with more mature speech production [31, 58, 59]. However, a trade-off in having a higher degree of speech movement stability and coordination may be a reduction in the flexibility of motor planning and/or breadth of motor solutions for a given task. In a study of Bengali–English bilingual speakers, speakers who learned English at a later age and had a lower level of English proficiency had higher speech movement stability, which may reflect a lower degree of flexibility in speech motor control [60]. Similarly, typically-developing infants have more variability (e.g., less stability and coordination) in their postural swaying during sitting than infants with CP, suggesting that the typically-developing infants are able to draw on a greater number of movement strategies to complete the task [56]. There is a potential trade-off between the flexibility of generating multiple solutions to complete a task and reliably reproducing previous movements. Further research is needed to determine the optimal range of interarticulator coordination needed to produce speech in an intelligible manner.

Articulatory and linguistic task demands generally affect spatiotemporal coordination

In addition to consistent group effects, articulatory and linguistic task demands were observed to influence the spatial coupling of the oral articulators. Both groups demonstrated higher spatial and temporal coupling of the jaw and lower lip for the sentences, which had the greatest language formulation demands, than the syllable repetition or the DDK tasks. Children with CP also demonstrated greater spatial coupling for sentences than DDK and greater temporal coupling for sentences than the DDK or syllables for the upper and lower lips.

These findings suggest that speech motor control is more likely to be influenced by articulatory and linguistic task demands for children with CP than their TD peers and that the production of simple sentences appears to facilitate the greatest degree of interarticulator coordination for children with CP. One explanation for this finding may be that sentences are produced in daily communicative interactions and this task was most familiar and practiced for all participants. In contrast, repeating syllables or completing a DDK task is likely novel, unfamiliar, and abstract, particularly because these tasks lack semantic content.

An alternate explanation may be that simple sentences are a preferred task. Previous studies have demonstrated that simple sentences are more stable in the speech movement patterns as compared to more syntactically complex sentences [58]. These observations suggest that increasing or decreasing the articulatory and/or linguistic demands from a simple sentence decreases speech movement stability and coordination for both children with CP and their TD peers. However, further research with more specific manipulations of articulatory and linguistic complexity is required to determine the relative contribution of articulatory and linguistic task demands to spatiotemporal coordination of the lips and jaw during speech production in both children with CP and their typically-developing peers.

Reduced interarticulator coordination may underlie speech intelligibility deficits

Both groups demonstrated a range of intelligibility scores. This variability was expected in the CP group because of the inclusion of participants with a range of speech difficulties, from those with no dysarthria to those with severe dysarthria. Somewhat surprisingly there was a relatively large range of intelligibility scores in the typically-developing children as well, though this range was smaller than the range in intelligibility for the CP group. A couple of the younger TD participants had lower than expected intelligibility scores, primarily due to voicing errors (e.g., produced “d” when the word included a “t”). Because the all the phonemes in a word must be produced correctly to be scored as intelligible, these voicing errors diminished the intelligibility scores.

Several significant associations were observed between measures of both single-word and sentence intelligibility and measures of spatial and temporal coordination for the children with CP, reflecting the impact of spatiotemporal coordination between articulators on intelligibility. These correlations also suggest that the presence of dysarthria may negatively impact interarticulator coordination. Poorer intelligibility scores, which characterized the children with dysarthria, were shown to be correlated with reduced spatial (lower correlation coefficients) and temporal (higher lags) coordination. This finding is similar to previous work that has demonstrated that deficits in speech motor control are linked to intelligibility in children with speech sound disorders [24].

Similarly, there were significant correlations between intelligibility and interarticulator coordination for the typically-developing peers. However, the number of significant association were smaller for the typically-developing peers than for the CP group, though this may have been due to the somewhat smaller range of intelligibility scores seen in this group. The finding that interarticulator coordination is associated with intelligibility suggests that more severe movement deficits caused by CP may underlie the speech impairments in this population. Potentially, measures of spatiotemporal coordination of articulators may be used to further distinguish communication sub-groups of children with dysarthria.

The patterns of correlations indicate the difference in the relative importance of articulator pairs in the motor execution of speech production. The significant correlations were between the measures of the spatiotemporal coordination of the upper lip and jaw and the upper and lower lips. These two pairs of articulators represent constrictions specified in speech production [34, 35], particularly in utterances loaded with bilabial segments. In contrast, the coordination between the lower lip and jaw is likely not specified during speech production because the movements of these two articulators do not result in a constriction of the vocal tract. Perhaps not surprisingly, the spatiotemporal coordination of the lower lip and jaw were not significantly associated with intelligibility. This finding may suggest that reduced interarticulator coordination, especially when a pair of articulators plays a critical role in reaching articulatory targets, may negatively impact speech intelligibility observed in a population with neuro-motor disorders, such as speakers with CP.

Implications

One challenge in advancing our understanding of CP is the heterogeneity of the disorder. Individuals with CP vary in the signs, symptoms and severity of the disorder [2]. Kinematic measures, which can highlight differences in articulatory movements that may be missed by phonetic transcription and acoustic analyses, can be used to complement existing communication classification schemes [5] and may provide researchers and clinicians with new avenues for assessment and intervention. The current investigation included children with CP with mild or no dysarthria as well as children with more moderate or severe dysarthria; however, many of these children had reduced spatiotemporal coordination as compared to their TD peers. Similarly, children with CP classified as having no speech impairments had reductions in speech intelligibility for longer utterances as compared to TD children [8]. Taken together with the current findings, these results suggest that the underlying neuromotor deficits evident in children with CP may negatively impact their speech development [8].

Limitations and future directions

Although the current study provides important preliminary information about speech motor control in individuals with CP, some limitations exist. This study examined how the interarticulator coordination in children with CP may relate to the severity of dysarthria; however the relatively small sample does not allow for the determination if children with dysarthria differ in their interarticulator coordination from those who do not have dysarthria. Similarly, whether children with CP but without dysarthria are more similar to their typically-developing peers or to children with CP and dysarthria could not be determined. Due to the degree of heterogeneity in the population, future work will need to include a larger number of participants in order to better understand how the speech movement characteristics of this population may ultimately impact intelligibility. The inclusion of clinical measures of speech motor control may also help to connect clinical observations and judgments to the underlying movement patterns of these children. In addition, the current investigation primarily focused on the lips and jaw. Information regarding other articulators, particularly the tongue, will provide further insight into the articulatory patterns and strategies that may be used in this population. Further manipulation of articulator and linguistic demands (e.g., manipulating syntactic complexity which maintaining utterance length such as a paradigm used in [58]) may be included to examine the relative contribution of each variable on speech motor control in this population.

Conclusion

This investigation aimed to provide preliminary insights on the speech motor control of children with CP and the effects of linguistic demands on motor control. Speakers with CP generally show a lower degree of spatial and temporal interarticulator coordination. In addition, speech movements embedded within a simple sentence are generally produced with greater spatiotemporal coordination as compared to syllables or DDK. These results suggest that relations between language and speech motor control in individuals with CP may potentially account for some of the speech impairments observed in this population.

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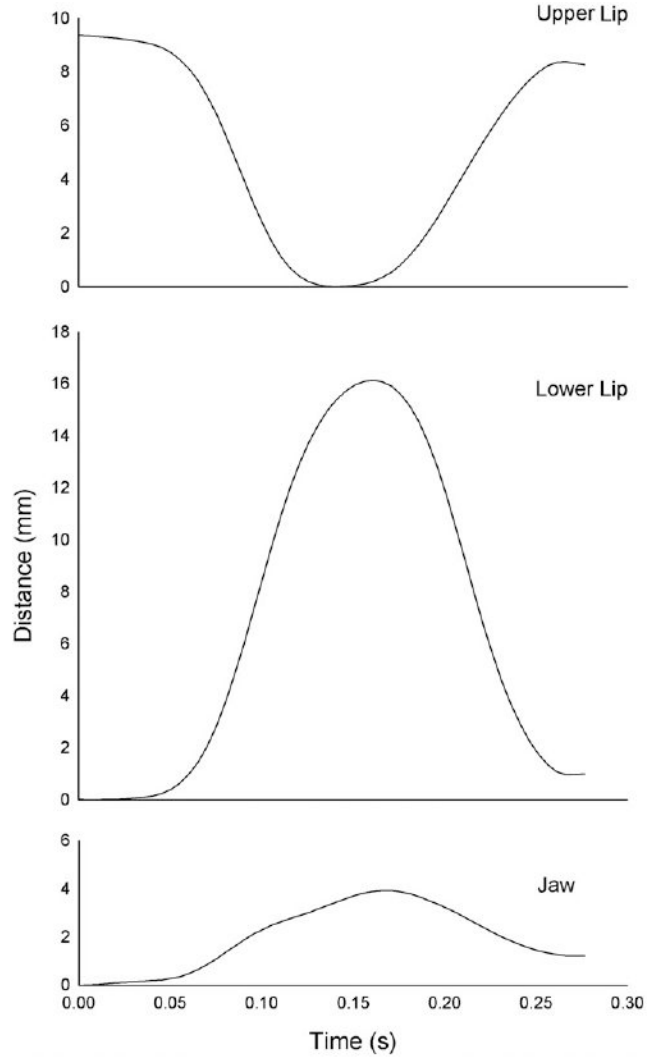

Figure 1.

Example of the upper lip, lower lip, and jaw movement traces during the production of /ʌbʌ/.

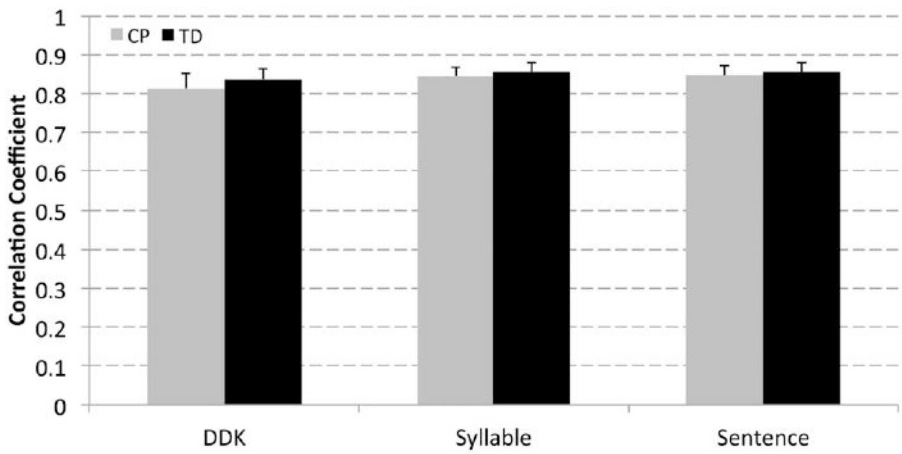

Figure 2.
Means and standard errors of the spatial coupling of the upper lip and jaw for the diadochokinetic (DDK), syllable and sentence tasks.

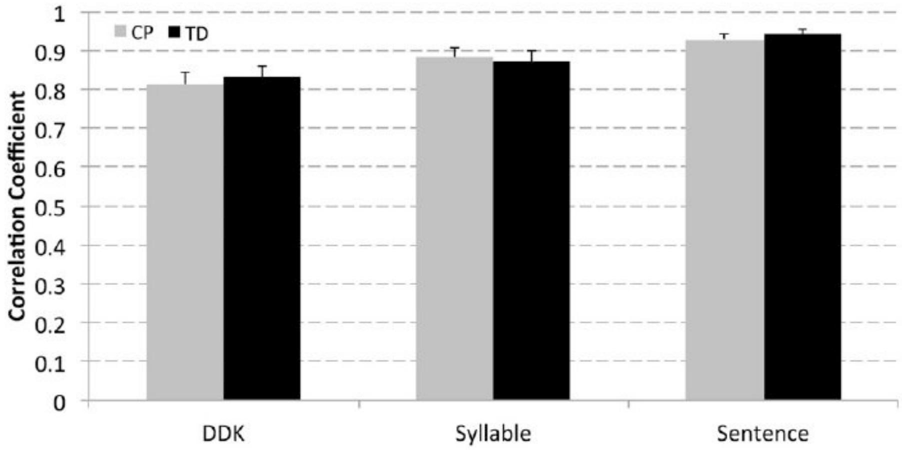

Figure 3.
Means and standard errors of the spatial coupling of the lower lip and jaw for the diadochokinetic (DDK), syllable and sentence tasks.

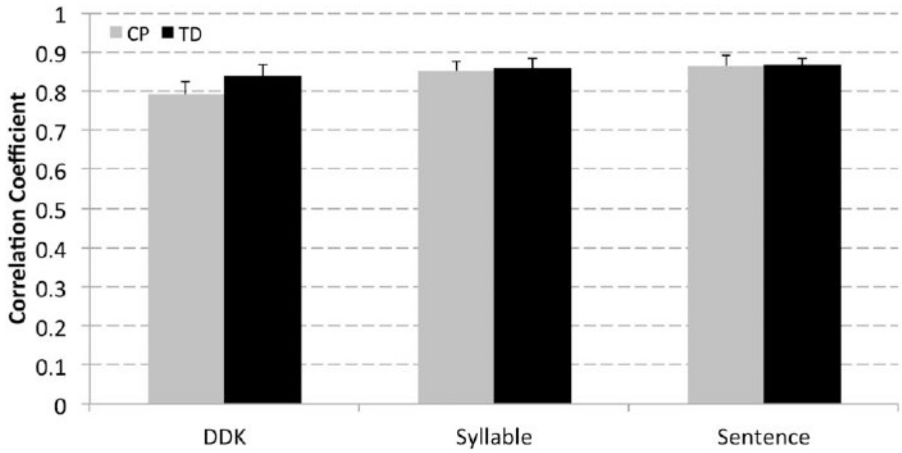

Figure 4.

Means and standard errors of the spatial coupling of the upper and lower lips for the diadochokinetic (DDK), syllable and sentence tasks.

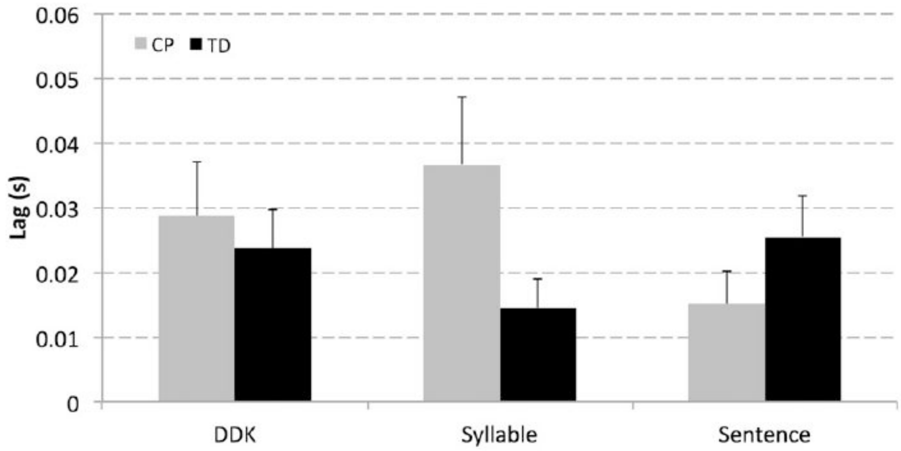

Figure 5.
Means and standard errors of the temporal coupling of the upper lip and jaw for the diadochokinetic (DDK), syllable and sentence tasks.

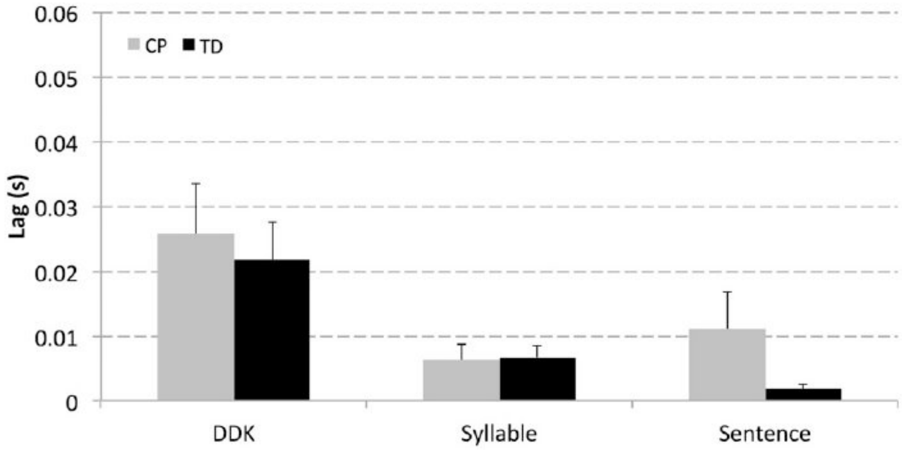

Figure 6.

Means and standard errors of the temporal coupling of the lower lip and jaw for the diadochokinetic (DDK), syllable and sentence tasks.

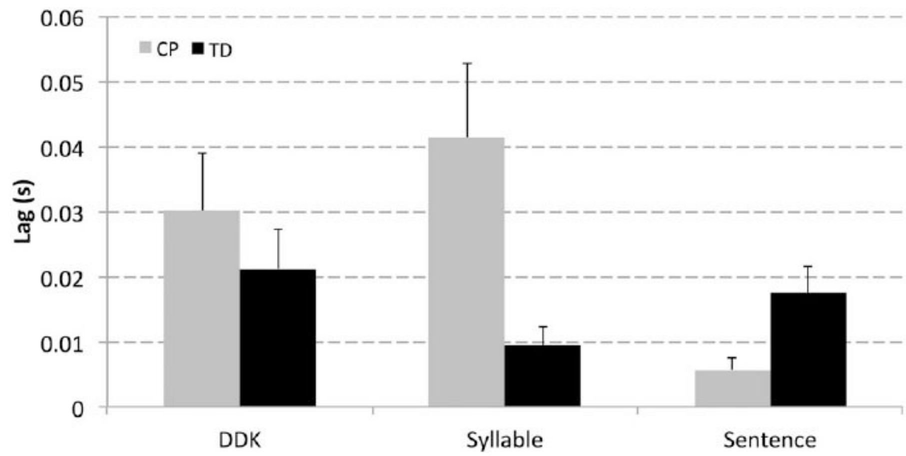

Figure 7.

Means and standard errors of the temporal coupling of the upper and lower lips for the diadochokinetic (DDK), syllable and sentence tasks.

Table I

Age, sex, language scores, intelligibility scores, and speech characteristics for each participant with cerebral palsy (CP).

Speaker	Age	Sex	CP Type	GMFCS	CELF CLS	Word Intell.	Sentence Intell.	Speech Characteristics
1	4;8	F	Spastic quadriplegia	V	106	23%	16%	Spastic dysarthria: slow rate, imprecise articulation, reduced loudness, mild hypernasality, mild strain-strangled voice, short breath groups, voice breaks
2	5;4	M	Spastic hemiplegia, Dandy Walker var.	V	75	72%	N/A	Spastic dysarthria: slow rate, distorted vowels, imprecise articulation, reduced pitch, reduced loudness, strain-strangled voice, hypernasality, short breath groups
3	6;6	M	Spastic diplegia	III	106	72%	83%	Spastic dysarthria: slow rate, mild monopitch, reduced loudness; /s/ articulation error
4	6;9	F	Spastic quadriplegia	IV	62	N/A	39%*	Spastic dysarthria: slow rate, hypernasality, imprecise articulation, distorted vowels, reduced loudness, short breath groups, strain-strangled voice
5	7;5	F	Spastic diplegia	II	102	76%	86%	Spastic dysarthria: reduced pitch, mild strained-strangled voice, hypernasality, glottal fry
6	8;2	M	Spastic diplegia	II	98	80%	77%	Mild dysarthria: occasional glottal fry, slow rate; /s/ articulation error
7	9;0	M	Spastic hemiplegia	II	121	89%	96%	No detectable dysarthria; mild /s/ articulation error
8	9;9	M	Spastic	III	67	79%	76%	Spastic dysarthria: mild strained-strangled voice, hypernasality
9	10;2	F	Spastic	III	111	77%	98%	Mild dysarthria: hyponasality, reduced pitch
10	10;7	M	Spastic quadriplegia	IV	127	85%	96%	No detectable dysarthria; /r/ articulation error
11	12;4	M	Spastic diplegia	II	112	89%	96%	No detectable dysarthria; some glottal fry
12	15;0	F	Spastic diplegia	II	129	82%	93%	No detectable dysarthria

Language scores are the standard scores from the Core Language Scale (receptive and expressive language) of the CELF-P2 (participants aged four years), and CELF-4 for other participants. Word and sentence intelligibility from the TOCS+ for participants aged 9;11 and under and from the SIT for participants 10;0 and older. CELF = Clinical Evaluation of Language Fundamentals; GMFCS = Gross Motor Functional Classification Scale; SIT = Speech Intelligibility Test; TOCS+ = Test of Children's Speech +.

*Sentence intelligibility estimated from narrative re-tell sample.

Table II

Age, sex, language scores and intelligibility scores for typically-developing age- and sex-matched participants.

Speaker	Age	Sex	CELF CLS	Word Intelligibility	Sentence Intelligibility
13	4;7	F	106	59%	53%
14	5;7	M	93	57%	77%
15	6;2	M	106	77%	61%
16	7;4	F	94	84%	88%
17	8;2	F	94	86%	94%
18	8;4	M	98	89%	93%
19	9;0	M	121	91%	92%
20	9;4	M	124	90%	97%
21	10;10	F	104	78%	98%
22	10;11	M	127	92%	96%
23	13;2	M	104	95%	99%
24	15;7	F	124	90%	98%

Language scores are the standard scores from the Core Language Scale (receptive and expressive skills) of the CELF-P2, for the participants aged four years, and CELF-4 for all other participants. Word and sentence intelligibility are from the TOCS+ for participants aged 9;11 and under and from the SIT for participants 10;0 and older. CELF = Clinical Evaluation of Language Fundamentals.

Table III

Means and standard deviations of absolute value of the cross-correlation coefficients for each articulator pair and task for each participant.

	Upper lip and jaw			Jaw and lower lip			Upper lip and lower lip		
Speaker	DDK	Syllable	Sentence	DDK	Syllable	Sentence	DDK	Syllable	Sentence
1	0.77 (0.17)	0.72 (0.05)	0.73 (0.08)	0.65 (0.12)	0.89 (0.09)	0.85 (0.07)	0.66 (0.12)	0.67 (0.06)	0.78 (0.13)
2	0.76 (0.14)	0.85 (0.07)	0.73 (0.14)	0.86 (0.09)	0.93 (0.07)	0.91 (0.06)	0.8 (0.05)	0.89 (0.07)	0.72 (0.15)
3	0.79 (0.13)	0.74 (0.09)	0.76 (0.13)	0.79 (0.09)	0.86 (0.1)	0.92 (0.06)	0.73 (0.09)	0.77 (0.09)	0.78 (0.15)
4	0.9 (0.07)	0.82 (0.06)	0.9 (0.04)	0.92 (0.09)	0.93 (0.08)	0.91 (0.07)	0.86 (0.08)	0.78 (0.1)	0.83 (0.18)
5	0.78 (0.13)	0.94 (0.08)	0.86 (0.08)	0.77 (0.12)	0.93 (0.09)	0.89 (0.07)	0.75 (0.13)	0.94 (0.08)	0.9 (0.07)
6	0.85 (0.12)	0.87 (0.11)	0.94 (0.06)	0.77 (0.13)	0.84 (0.12)	0.97 (0.02)	0.82 (0.14)	0.84 (0.1)	0.92 (0.07)
7	0.81 (0.19)	0.79 (0.11)	0.89 (0.05)	0.85 (0.1)	0.75 (0.13)	0.87 (0.07)	0.76 (0.16)	0.84 (0.11)	0.91 (0.06)
8	0.88 (0.08)	0.92 (0.06)	0.7 (0.18)	0.87 (0.07)	0.9 (0.07)	0.93 (0.04)	0.88 (0.07)	0.93 (0.07)	0.79 (0.17)
9	0.84 (0.15)	0.85 (0.07)	0.97 (0.02)	0.84 (0.12)	0.93 (0.05)	0.97 (0.04)	0.83 (0.16)	0.89 (0.09)	0.93 (0.06)
10	0.65 (0.19)	0.86 (0.08)	0.95 (0.03)	0.71 (0.21)	0.93 (0.08)	0.96 (0.03)	0.67 (0.2)	0.92 (0.04)	0.98 (0.01)
11	0.83 (0.12)	0.89 (0.11)	0.95 (0.06)	0.83 (0.08)	0.84 (0.08)	0.98 (0.02)	0.82 (0.09)	0.84 (0.12)	0.97 (0.03)
12	0.89 (0.1)	0.88 (0.09)	0.8 (0.13)	0.9 (0.07)	0.88 (0.1)	0.97 (0.01)	0.89 (0.09)	0.88 (0.15)	0.85 (0.13)
13	0.94 (0.04)	0.86 (0.09)	0.63 (0.06)	0.95 (0.06)	0.91 (0.06)	0.97 (0.02)	0.96 (0.04)	0.95 (0.06)	0.67 (0.08)
14	0.83 (0.11)	0.64 (0.09)	0.76 (0.12)	0.77 (0.16)	0.83 (0.14)	0.9 (0.06)	0.77 (0.14)	0.64 (0.13)	0.78 (0.03)
15	0.87 (0.12)	0.79 (0.11)	0.85 (0.07)	0.86 (0.06)	0.91 (0.09)	0.91 (0.07)	0.89 (0.08)	0.8 (0.15)	0.83 (0.08)
16	0.83 (0.08)	0.89 (0.11)	0.93 (0.05)	0.82 (0.17)	0.88 (0.08)	0.97 (0.04)	0.82 (0.16)	0.89 (0.09)	0.95 (0.04)
17	0.75 (0.12)	0.82 (0.06)	0.93 (0.06)	0.74 (0.13)	0.83 (0.05)	0.96 (0.03)	0.78 (0.14)	0.97 (0.04)	0.97 (0.02)
18	0.79 (0.07)	0.9 (0.07)	0.72 (0.11)	0.79 (0.07)	0.95 (0.05)	0.91 (0.05)	0.79 (0.07)	0.86 (0.11)	0.78 (0.08)
19	0.7 (0.08)	0.95 (0.07)	0.88 (0.15)	0.72 (0.09)	0.88 (0.14)	0.91 (0.04)	0.73 (0.12)	0.94 (0.08)	0.83 (0.09)
20	0.89 (0.08)	0.86 (0.06)	0.92 (0.09)	0.91 (0.07)	0.84 (0.12)	0.95 (0.04)	0.91 (0.07)	0.81 (0.12)	0.9 (0.13)
21	0.76 (0.13)	0.89 (0.09)	0.84 (0.04)	0.78 (0.13)	0.86 (0.13)	0.92 (0.04)	0.78 (0.13)	0.83 (0.07)	0.91 (0.03)
22	0.93 (0.09)	0.88 (0.12)	0.94 (0.07)	0.9 (0.07)	0.89 (0.08)	0.98 (0.02)	0.89 (0.1)	0.91 (0.09)	0.95 (0.06)
23	0.76 (0.14)	0.89 (0.09)	0.9 (0.09)	0.76 (0.14)	0.9 (0.09)	0.95 (0.04)	0.76 (0.14)	0.89 (0.09)	0.91 (0.06)
24	0.98 (0.01)	0.87 (0.06)	0.94 (0.05)	0.98 (0.01)	0.82 (0.06)	0.97 (0.01)	0.98 (0.01)	0.82 (0.04)	0.93 (0.04)

Table IV

Means and standard deviations of absolute value of the lags for each articulator pair and task for each participant.

	Upper lip and jaw			Jaw and lower lip			Upper lip and lower lip		
Speaker	DDK	Syllable	Sentence	DDK	Syllable	Sentence	DDK	Syllable	Sentence
1	0.07 (0.05)	0.11 (0.04)	0.04 (0.03)	0.05 (0.05)	0 (0.01)	0.04 (0.05)	0.05 (0.05)	0.12 (0.05)	0.01 (0.01)
2	0.01 (0.01)	0.01 (0.01)	0.03 (0.02)	0.01 (0.01)	0 (0.01)	0.02 (0.06)	0.03 (0.05)	0.02 (0.06)	0.01 (0.01)
3	0.04 (0.03)	0.06 (0.04)	0.03 (0.03)	0.03 (0.04)	0 (0.01)	0 (0.01)	0.04 (0.03)	0.05 (0.05)	0.01 (0.01)
4	0.02 (0.03)	0.1 (0.06)	0.01 (0.01)	0 (0.01)	0 (0.01)	0 (0)	0.03 (0.04)	0.13 (0.07)	0.01 (0.01)
5	0.02 (0.03)	0 (0)	0.02 (0.02)	0.03 (0.03)	0 (0.01)	0.04 (0.05)	0.03 (0.04)	0 (0)	0 (0.01)
6	0.01 (0.01)	0.03 (0.05)	0.01 (0.02)	0.03 (0.03)	0.01 (0.01)	0 (0)	0.02 (0.01)	0.07 (0.08)	0.01 (0.01)
7	0.02 (0.03)	0.02 (0.04)	0.01 (0.01)	0.02 (0.03)	0.02 (0.01)	0.03 (0.05)	0.03 (0.02)	0.04 (0.04)	0.01 (0.01)
8	0.01 (0.02)	0.01 (0.04)	0.02 (0.02)	0.01 (0.02)	0.01 (0.01)	0 (0)	0 (0.01)	0 (0)	0.01 (0.01)
9	0.03 (0.04)	0.04 (0.05)	0 (0)	0.03 (0.03)	0 (0.01)	0 (0)	0.02 (0.04)	0.02 (0.04)	0 (0)
10	0.05 (0.03)	0.01 (0.01)	0 (0.01)	0.05 (0.03)	0 (0)	0 (0)	0.05 (0.03)	0 (0)	0 (0)
11	0.04 (0.03)	0.03 (0.05)	0 (0)	0.04 (0.02)	0.01 (0.01)	0 (0)	0.04 (0.02)	0.02 (0.03)	0 (0)
12	0.02 (0.04)	0.02 (0.03)	0.01 (0.03)	0.02 (0.02)	0 (0)	0 (0)	0.01 (0.02)	0.03 (0.05)	0 (0)
13	0 (0)	0.01 (0.02)	0.06 (0.03)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0.01)	0.03 (0.03)
14	0.02 (0.03)	0.04 (0.02)	0.06 (0.04)	0.03 (0.04)	0.01 (0.01)	0.01 (0.01)	0.02 (0.02)	0.02 (0.01)	0.04 (0.03)
15	0.02 (0.02)	0.02 (0.02)	0.03 (0.03)	0.02 (0.02)	0 (0)	0.01 (0.01)	0.01 (0.02)	0.02 (0.01)	0.03 (0.02)
16	0.01 (0.03)	0 (0)	0.01 (0.01)	0.01 (0.02)	0 (0.01)	0 (0)	0.03 (0.04)	0.01 (0.01)	0 (0.01)
17	0.03 (0.03)	0.03 (0.02)	0 (0.01)	0.03 (0.03)	0.02 (0.01)	0 (0)	0.02 (0.02)	0 (0)	0 (0)
18	0.05 (0.02)	0.01 (0.02)	0.06 (0.03)	0.05 (0.02)	0 (0)	0 (0)	0.05 (0.02)	0.01 (0.01)	0.04 (0.01)
19	0.05 (0.01)	0.01 (0.02)	0.02 (0.03)	0.05 (0.02)	0.01 (0.01)	0 (0.01)	0.04 (0.02)	0 (0.01)	0.02 (0.02)
20	0.01 (0.03)	0.02 (0.02)	0.01 (0.02)	0.01 (0.03)	0.01 (0.01)	0 (0)	0.01 (0.01)	0.02 (0.01)	0.02 (0.02)
21	0.05 (0.03)	0.01 (0.02)	0.03 (0.03)	0.02 (0.03)	0.01 (0.01)	0 (0)	0.03 (0.04)	0.02 (0.02)	0.01 (0.01)
22	0.01 (0.03)	0.01 (0.02)	0 (0)	0.01 (0.02)	0 (0)	0 (0)	0.01 (0.03)	0 (0.01)	0 (0)
23	0.03 (0.02)	0 (0)	0.02 (0.03)	0.03 (0.02)	0 (0)	0 (0)	0.03 (0.02)	0 (0)	0.01 (0.02)
24	0 (0)	0 (0)	0 (0)	0 (0)	0.01 (0.01)	0 (0)	0 (0)	0.01 (0)	0 (0)

Table V

Pearson correlations between cross-correlation coefficient and lag values for each articulator pair and task and word and sentence intelligibility scores for participants with CP.

Articulator Pair	Task	Cross-correlation coefficient and word intelligibility	Cross-correlation coefficient and sentence intelligibility	Lag and word intelligibility	Lag and sentence intelligibility
Upper lip and jaw	DDK	0.17	−0.13	−0.59	−0.34
	Syllable	0.60*	0.52	−0.82**	−0.85**
	Sentence	0.51	0.42	−0.74**	−0.64*
Jaw and lower lip	DDK	0.65*	0.13	−0.30	0.07
	Syllable	−0.23	0.31	0.35	0.24
	Sentence	0.60^	0.60	−0.49	−0.29
Upper lip and lower lip	DDK	0.51	0.23	−0.42	−0.23
	Syllable	0.74*	0.75**	−0.75**	−0.84**
	Sentence	0.54	0.63*	−0.56	−0.78**

* $p<0.05$;

** $p<0.01$;

^ $p = 0.053$.

Table VI

Pearson correlations between cross-correlation coefficient and lag values for each articulator pair and task and word and sentence intelligibility scores for typically-developing participants.

Articulator pair	Task	Cross-correlation coefficient and word intelligibility	Cross-correlation coefficient and sentence intelligibility	Lag and word intelligibility	Lag and sentence intelligibility
Upper lip and jaw	DDK	−0.22	−0.33	0.25	0.39
	Syllable	0.69 *	0.42	−0.52	−0.25
	Sentence	0.71**	0.67 *	−0.71 **	−0.58 *
Jaw and lower lip	DDK	−0.13	−0.29	0.16	0.23
	Syllable	0.09	−0.31	−0.16	0.25
	Sentence	0.31	0.19	−0.39	−0.41
Upper lip and lower lip	DDK	−0.14	−0.36	0.31	0.35
	Syllable	0.41	0.09	−0.36	−0.09
	Sentence	0.68 *	0.75 **	−0.61 *	−0.56

* $p<0.05$;

** $p<0.01$.