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Instrumental articulatory techniques investigating lingual variability in typically developing children: A scoping review

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ABSTRACT

This scoping review was designed to provide an overview of instrumental articulatory techniques used to investigate lingual variability in typically developing children. Despite extensive research on phonological acquisition, the development of speech motor control in children is less understood. Kinematic studies in this area have focused on children under 10, but adolescents' speech and the attainment of adult-like motor control remains under-researched. This review includes studies using instrumental techniques such as Ultrasound Tongue Imaging (UTI), Electropalatography (EPG) and Electromagnetic Articulography (EMA) to measure spatial and temporal articulatory features using a variety of metrics. Studies show greater articulatory variability in children compared to adults; however, inconsistencies in methodologies and participant samples limit the ability to synthesise findings effectively. Future research should focus on longitudinal studies spanning childhood and adolescence, using techniques that are easily incorporated into clinical practice. A detailed understanding of typical articulatory variability across different age ranges is crucial for identifying speech disorders and improving clinical interventions.

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Introduction

Speech is one of the most complex cognitive and motor skills children acquire. While much work has been undertaken to determine the path of phonological acquisition in children, particularly in English, comparatively little is understood about how children develop adult-like speech motor control. Cross-linguistically, most children have acquired all the consonants of their home language by 5 years (McLeod & Crowe, 2018), and early work on the developmental sequence of speech motor control documented the linguistic and phonetic properties of infant babbling (Smith & Goffman, 1998). In contrast, longitudinal accounts of speech motor development are scarce, though prevailing theories support a non-linear trajectory (Nip et al., 2009). Moreover, new techniques have challenged our previous understandings of how children develop fully mature speech motor control. Kinematic studies generally indicate a reduction in the variability of speech movements over time; however, these studies have primarily concentrated on children under the age of 10. It is understood that vowels are less motorically complex than consonants, which in turn have a developmental hierarchy from less to more complex, for example, English rhotics are motorically complex since they are produced

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with a dual constriction and, therefore, they are later acquired (Kabakoff et al., 2023). This will potentially influence the variability we should expect to see at any given age, with earlier acquired sounds being well practised and possibly more stable as a result. Less is known about the developmental trajectory of adolescents' speech and when exactly adult-like speech motor control is reached (Goffman & Smith, 1999; Green et al., 2000, 2002; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Watkin & Fromm, 1984). Studies that have looked at the adolescent population indicate that speakers continue to refine the temporal and spatial aspects of their speech well into late adolescence (Schötz et al., 2013; Smith & Zelaznik, 2004; Walsh & Smith, 2002). This finding would therefore indicate a more protracted development that goes beyond the typical completion of the phonological inventory, which is usually complete and error free by the age of six in English-speaking children (Dodd et al., 2003).

Estimates of speech motor control abilities can be quantified in several ways, including via auditory-perceptual ratings; acoustic measurements obtained from the auditory signal; or via articulatory measurements collected with various forms of instrumentation. For example, Speech and Language Therapists (SLTs) might use maximum performance tasks, such as rapidly alternating syllables (diadochokinetic tasks such as repeating /pətəkə/ at maximum rate). In these tasks, children with motor speech disorders tend to have slower rates, or less accurate productions, than typically developing children, and typically developing children show increased rate and accuracy with age (Williams & Stackhouse, 2000).

This current scoping review concerns itself with articulatory variability, which has been well studied as an indicator of immature speech motor control (Wohlert & Smith, 2002). In particular, we are interested in biomechanical variability, which is distinct from the variability caused by the coarticulatory effects seen when neighbouring sounds exert influence over the articulatory gestures of others. In typical speech, both are a product of the speech system's adaptability to maintain natural and fluent speech despite small changes in articulatory patterns. There is no firm consensus on whether children coarticulate more or less than adults, however, when considering disordered speech, we predict those that have increased biomechanical variability due to poor motor speech control, will also have differences in coarticulation, as evidenced by one of the defining features of Childhood Apraxia of Speech being 'lengthened and disrupted coarticulatory transitions between sounds and syllables' (Childhood Apraxia of Speech, 2007).

The definition of variability is not straightforward. In the speech disorder literature, there is ongoing confusion about the terms 'inconsistency/consistency' and 'variability', with the terms often used interchangeably (Holm et al., 2007). Both terms lack clear operational definitions (Marquardt et al., 2004). Definitions can vary between the literature focusing on phonological development and the literature focusing on motor-speech development. Inconsistency is most often used to describe disordered speech, e.g. in children with Childhood Apraxia of Speech (CAS) and Inconsistent Phonological Disorder (IPD), however, variability has also been used to describe both disordered inconsistency and the inconsistency associated with speech development in typical children.

Holm et al. (2007) suggest that 'Variability can be defined as repeated productions that differ, with the variability attributed to factors described in normal acquisition and use of speech' (Holm et al., 2007, p. 468). In this review, we define this biomechanical variability in speech motor control as sub-phonemic. That is, repeated productions of the same phonetic target, which are produced with variability in the articulatory gesture, that do not lead to a change in phonemic category. In other words, repeated productions, which might be transcribed the same using broad phonemic transcription. For example: /t/ might be produced by a child variably as [t, tʰ, t̺, t̪], even when the surrounding phonetic context remains constant. In this way, *variability* contrasts with *inconsistency* as defined in Inconsistent Phonological Disorder (Dodd, 2013), where repeated productions of the same lexical item can contain entirely different phonemes, for example, 'parrot' produced as [pawəʔ, dʌbə, wabət]. In the case of Inconsistent Phonological Disorder, the difficulty is therefore with phonological planning, not with speech motor control. This type of variability is also distinct from allophonic variation or variations in the articulatory gesture due to co-articulation. For example, an adult speaker with mature speech motor control produces /k/ in the word 'car' at a more posterior place of articulation than the /k/ in 'key' because of the anticipatory coarticulatory effect of the vowel. This type of variation is therefore applied in a consistent manner, is an indication of mature speech motor control, and is not the topic of this review.

In speakers with speech motor control difficulties, biomechanical variability may be subtle and can only be detected using instrumental acoustic or articulatory techniques. However, this kind of instrumental evidence is scarce due to the difficulties of collecting accurate articulatory data from young children. Increased lingual variability has also been identified in the speech of children with speech sound disorders (SSD) (Vick et al., 2014); however, without consistent data from typically developing children (TD), we cannot accurately interpret levels of variability found in children with different types of SSDs. Having a baseline is important, because increased variability is said to be a hallmark of motor speech immaturity, or disorder, and children with motor speech disorders need different treatments from children with phonological disorders, such as Inconsistent Phonological Disorder.

Measuring articulatory variability

Currently, phonetic transcription is the standard assessment practice for SLTs diagnosing SSDs, despite issues of inter-rater consistency (Howard, 2004; Sell, 2005). While transcription is sufficient for measuring inconsistency, it may be inadequate for measuring variability. Instrumental articulatory techniques, such as Ultrasound Tongue Imaging (UTI), have been shown to increase interrater reliability and the detection of subtle motor errors, such as increased lingual variability (Cleland et al., 2020). The identification of this increase in variability is likely to influence differential diagnosis and subsequent therapy selection, as those who have been previously thought to have an SSD of a phonological nature may, in fact, have a subtle motor speech issue (Vick et al., 2014). Despite some children being described as having increased variability, most studies do not use variability in the speech of typically developing children as a point of comparison.

Acoustic studies of speech acquisition have also been important for uncovering the developmental trajectory of speech motor control. Early studies found that children present with more durational variation compared to adult speech (Smith, 1978). Kent and Forner (1980) suggest durational variability stabilises by the age of 11 or 12, as does voice onset time. However, acoustic studies are limited insofar as they cannot measure the movements of the articulators directly, potentially missing acoustically covert variation. Therefore, it is crucial to also examine the articulatory, as well as acoustic, aspects of speech motor control, which can be undertaken with the use of articulatory instrumental technology.

Articulatory instrumental techniques

Well-established instrumental techniques in speech motor control research are: Electropalatography (EPG: Lee et al., 2023), Electromagnetic Articulography (EMA: Rebernik et al., 2021) and, more recently, Ultrasound Tongue Imaging (UTI: Rebernik et al., 2021). Theoretically, other imaging techniques such as Magnetic Resonance Imaging (MRI) could aid in the detection of many types of sub-phonemic articulatory variation, although they are less well used due to practical issues such as low frame rate and low spatial resolution of MRI recordings with current recording protocols (Narayanan et al., 2004). Advancements in real-time MRI mitigate these issues, however they can be prohibitively expensive. Each of these techniques offers a unique perspective on articulatory movements.

Electropalatography

EPG measures tongue-palate contact (Dent et al., 1995) rather than tongue movement per se and can be used to visualise speech productions in the alveolar, postalveolar, palatal and velar regions of the oral cavity, as long as there is tongue-palate contact (i.e. it cannot visualise open vowels or post-velar articulations). This technique uses a well-established metric specifically designed to look at variability across repeated productions: the variability index (Lee et al., 2023), which measures how often each area of the hard palate (as measured using a fixed number of contact points) is contacted by the tongue on repeated productions.

Electromagnetic Articulography

In contrast, EMA uses small, lightweight sensors attached to a speaker's tongue, lips and jaw (and optionally the soft palate, though most speakers cannot tolerate this) to track real-time movement and conceptualise midsagittal inter-articulatory coordination. EMA can therefore measure variability in movement trajectories, including the velocity and acceleration of multiple articulators and their coordination, however this technique may be considered invasive for younger speakers. The sensor placement is limited to the anterior oral tract (Rebernik et al., 2021), which can show vowels, bilabial, labiodental, dental, alveolar and rarely palatal and velar sounds.

Ultrasound Tongue Imaging

Finally, UTI measures the shape and position of the surface of the tongue (mid-sagittal or coronal) using an ultrasound probe placed under the chin and optionally stabilised using a purpose-built headset. Certain measures are robust to head movement and therefore do not need stabilisation (Cleland, 2021). It therefore allows comparison of tongue contours across multiple repetitions, but it does not allow exact flesh-point tracking, nor measurement of lip movement, nor analysis of tongue-palate contact, thus limiting its use to vowels, alveolar, postalveolar, palatal, velar and rarely, uvular and pharyngeal sounds.

These three instrumental articulatory techniques are of particular interest as they can also be used to remediate speech motor disorders when they are used as biofeedback tools; *clinical relevance* is a key factor in the choice of the instrumentation we have reviewed. Each tool when used as biofeedback can incorporate customised articulatory targets for treatment, however, the degree of acceptable variability is not known. Knowing this information would enhance biofeedback intervention protocols. Given that the techniques of interest, apart from EMA, are limited to observing lingual information, we have only included studies which directly study the articulation of the tongue. VICON, a motion capture system that is used to record movement of the lips and jaw, can also be used to measure articulatory variability (Case & Grigos, 2016); however, it was excluded from this review as by its nature, it does not capture lingual articulation.

Given the differences in these key instrumental techniques, it is essential to review how each technique contributes to understanding of speech motor control and identify where methodological differences might lead to conflicting findings. The identification of increased variability compared to a typically developing baseline may be crucial for the SSD population to support SLTs in correctly diagnosing and treating this population. However, as a first step we need to understand what developmental articulatory variability looks like in the typical population. This makes it necessary to review the existing literature that describes this variability in TD children using instrumental techniques.

This paper is a scoping review of the literature on instrumental assessment of lingual articulatory biomechanical variability in typical speech development. We chose scoping, rather than systematic review, because the topic of articulatory variability is a diverse and emerging area. Given the diverse nature of study designs and methods available to study articulatory kinematics, a broader overview that a scope provides, which can identify potential research gaps, is more appropriate for this emerging field.

Methods

Design

The Joanna Briggs Institute (JBI) guidance and terms for scoping reviews (Peters et al., 2015) was used in the development of this review to allow for replication and to strengthen methodological rigour. The method is outlined below:

Objective/aim

To provide an overview of the current literature investigating lingual articulatory variability in typically developing children, using instrumental articulatory techniques, and with reference to these specific questions:

(1) How variable are typically developing children, and how does this change over the course of speech development?
(2) Which articulatory techniques, i.e. Ultrasound Tongue Imaging, Electropalatography, Electromagnetic Articulography and Magnetic Resonance Imaging, have been most used?
(3) What articulatory metrics, if any, do the authors implement?

Table 1. Table displaying search strategy of what databases and number of papers found in search.

Database	Search Strategy	Yield
EBSCOhost	(tongue* OR artic* OR lingual) (and) (variability* OR inconsist* OR motor) (and) (child* OR develop*) (and) spe* (and) (ultraso* OR electropalatograph* OR electromagnetic* OR magnetic resonance imaging) (and) (typical* OR norm*)	694

Scoping review objectives

- To explore which articulatory instrumental techniques are used to investigate variability.
- To determine the type of speech stimuli used in the assessment of variability.
- To determine which other articulators have been investigated with articulatory instrumentation.
- To explore how articulatory variability is measured in the current literature.

Inclusion criteria

- *Types of participants*: Typically developing children aged 3–18. Studies including adults and children with speech disorders were considered, if TD children within the specified age range were also included as a comparison group. Adult and disordered children's speech will be discussed in this review, only in relation to the development of typical child speech group contained within the same study.
- *Concept*: The sources included for review had to use a measure of lingual variability, made using an instrumental technique such as UTI, EMA, etc. Sources must provide detailed descriptions of articulatory variability metrics.
- *Context*: literature on this topic is scarce, so no timeframe was imposed. Resources must be available in English; however, sources from any country and language were included.
- *Type of sources*: Peer-reviewed journal articles that included detailed information about the variability metrics used and the method.
- *Search strategy*: Following Peters et al. (2015), an initial limited database search was conducted using SUPrimo, - the University of Strathclyde integrated library search service (University of Strathclyde, 2023), which includes multiple health-care and linguistic databases (see www.guides.lib.strath.ac.uk/az.php for full list of databases). The refined search strategy used is shown in Table 1. Hand searching of references was used to identify additional relevant sources.
- *Resource selection*: The PRISMA Scoping Review Extension (PRISMA-ScR) flowchart (Tricco et al. 2016) outlines the study selection process and is shown in Figure 1. The literature was screened for relevance by title, then abstract and finally by full text.

Results

Sources that met the inclusion criteria were read in full. They were then tabulated according to country of origin, participant information, methodology, metrics, speech stimuli and key findings (Tables 3–5).

A total of 586 articles (duplicates removed) were initially identified from the search (see Figure 1 for the selection process). The first author conducted the screening process, excluding articles by title and abstract based on the exclusion/inclusion criteria. The full texts of 23 articles were retrieved and were reviewed by the first author. Fifteen of the sources were included in the final scope. Articles were excluded that had no measure of token-to-token variability ($n = 6$), no TD participants ($n = 1$) and no measure on lingual variability ($n = 1$). Of the 15 articles included, the instrumental techniques used were: UTI ($n = 8$), EPG ($n = 3$) and EMA ($n = 4$). No papers using MRI met the inclusion criteria. Appendix displays a list of the included papers, and they are tabulated in Tables 4 and 5.

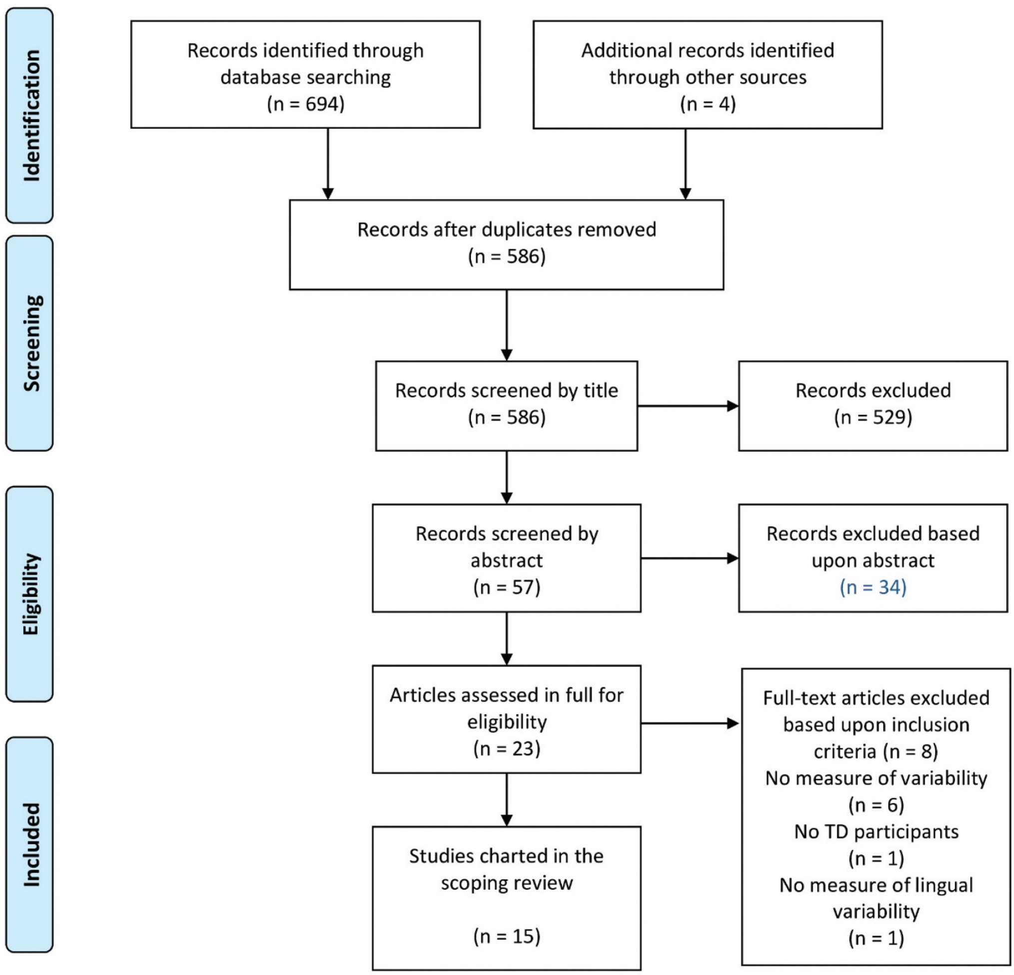

Figure 1. Prisma flow chart of the study screening process; maps out the number of records identified, included and excluded the reasons for their exclusion.

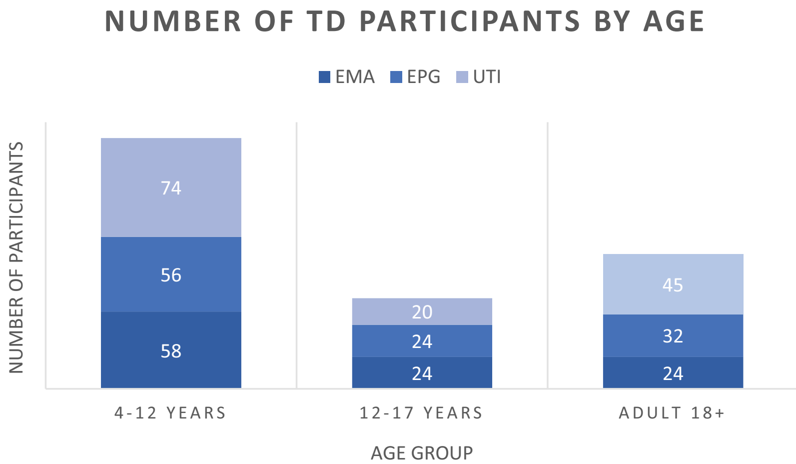

Figure 2. Bar chart showing number of typically developing participants by age group and instrumental technique.

Demographic information

Studies were conducted across six countries. The most produced by one country was Scotland ($n = 6$, 40%) followed by Australia ($n = 4$), Italy ($n = 2$), the USA ($n = 1$) Canada ($n = 1$) and the Netherlands ($n = 1$). Only four studies were of languages other than English: Italian ($n = 2$), Dutch ($n = 1$) and Canadian French ($n = 1$). About 73.4% of the studies were from four different English-dominant countries ($n = 11$).

The age range of the TD child speakers was 4–17 years across the articles. Some studies included an adult and/or a clinical comparison group, including speakers with stammering, childhood apraxia of speech, Down syndrome and cerebral palsy, which expanded the age range studied to 4–58 years. The total number of TD participants included across the 15 selected studies was 357 with 256 being TD children (see Figure 2).

Zharkova et al. (2011, 2012) UTI studies used the same participants but reported on different experimental materials. Although not reported, it would be reasonable to assume the same for all four EMA and EPG papers by Cheng et al. (2007, 2007a, 2007b) and Murdoch et al. (2012), as they report identical participant demographics. Considering this, it is estimated that there were 138 unique TD child participants across the 15 studies included in this review.

Metrics of variability

The quantitative metrics of articulatory variability that were used are described in Table 2. These form a mix of temporal and spatial metrics. The studies that used UTI investigate variability used spatial metrics, whereas the EPG and EMA studies used spatiotemporal metrics of variability. The mean Nearest Neighbour Distance (Zharkova et al., 2012) measure was a popular choice and was used in seven of the eight UTI studies from Italy, Canada and Scotland.

Table 2. Analysis metrics used across the studies categorised by instrument/articulators, descriptions, raw measures and reference.

Measure	Instrument/ Articulators	Description	Raw Measure	Source
Mean Nearest Neighbour Distance (mNND)	Ultrasound – tongue	NND measures the Euclidean distance between two specific points, or features, on the imaged tongue surface. The mean represents the average distance between equally distributed points along a pair of tongue curves. The mean Nearest Neighbour Distance measure quantifies the overall spatial differences between tongue shapes and was developed to study the effects of coarticulation. When used on repetitions of a sound that is within the same environment (e.g. /ta/ repeated 10 times) it can be used to quantity the spatial variability between the tongue contours of a sound. A higher mNND indicates greater variability.	The distance in millimetres (mm) between one point along the length of a sagittal tongue curve to its nearest neighbour point on another.	Zharkova et al. (2012)
Coefficient of Variation (CoV)	EPG – tongue/ palate contact Ultrasound-tongue EMA – tongue tip and body, and lower lip	A statistical measure used to express the relative variability, or dispersion, of articulatory movements. It is calculated by dividing the standard deviation of the measures by the mean and then multiplying by 100 to express as a percentage. A higher CoV indicates greater variability. Calculates variability of the segment duration of approach, closure/stable constriction, release phases.	EPG – Duration of utterance in milliseconds (ms) UTI – Dorsum Excursion Index in mm (degree of tongue dorsum bunching); LOCa-I in mm (Location of bunching along tongue contour). EMA – Distance (mm) travelled by coil attached to articulator; duration (ms) of movement by articulator; maximum speed mm per second (mm/s) of articulator; maximum acceleration and deceleration (mm/s^2) of articulator.	Mcauliffe et al. (2003)
Variability Index (VI)	EPG – tongue/ palate contact EMA – tongue tip and body, and lower jaw	Quantifies the level of spatiotemporal variation in the coordination between articulators' movements during multiple repetitions of a target consonant at a single point in time. A high variability index indicates low consistency across repetitions.	EPG – percentage across repetitions of contact to any given electrode. EMA – vertical displacement of articulators (mm)	Smith and Zelaznik (2004)
Spatiotemporal Index (STI)	EMA – tongue tip and body, and lower lip	Standard deviations of the time-and-amplitude-normalised displacement waveforms are completed at regular intervals of each repetition, giving 50 data points. The STI is the sum of these points. A higher STI indicates low consistency in articulatory movement (spatiotemporal stability). The STI captures the variability of an entire utterance.	Duration (ms); distance(mm) and speed(mm/s) of coils on articulators.	Smith et al. (1995)

(*Continued*)

Table 2. (Continued).

Measure	Instrument/ Articulators	Description	Raw Measure	Source
Zero-lag Correlations	EMA – tongue tip and lower jaw	Similar to the STI this measure describes the similarity between two time-and-amplitude normalised signals emitted by coils attached to the articulators at the same time point. Higher correlation values between the signals indicate more stable movements between repetitions. If correlation is low, it suggests the movements of the articulators are less synchronised.	Duration (ms); distance(mm) and speed(mm/s) of coils on articulators.	Green et al. (2002)

Articulators/Sounds investigated

EPG and UTI can only be used to describe the movements of the tongue. EMA, by nature, is the only instrument included in this scope that can give insight into multiple articulators and their interaction. In addition to the tongue, the EMA papers also reported on the jaw and lips.

Speech materials

The studies focused on the variability of consonants (within real and non-words) and vowels. Reported consonants included plosives: /p, t, d, k, g/, fricatives: /s, ʃ/ and the alveolar lateral approximant /l/. Lenoci and Ricci (2018) was the only paper that included voiced phones. Barbier et al. (2020) and Lenoci et al. (2021) chose instead to look at vowels using UTI and covered the French Canadian: /i/, /e/, /ɛ/, /a/, /u/ and the Italian: /a/, /i/, /u/, respectively.

The studies varied in elicitation methods, covering read or imitated single words, short carrier phrases, sustained vowels or sentences. This is important because task complexity influences the motoric demands on the speaker, and we would expect variability in TD children to increase as the complexity of the task does but then decrease through practice (Case & Grigos, 2021). Therefore, we could expect to see higher levels of variability within sentences compared to the lower demand tasks such as single words or sustained vowels. Another influencing factor on variability would be speech rate: we would expect increased variability with increased rate, even when complexity is similar (Lammert et al., 2018). However, none of the included studies chose to address the influence of speech rate on articulatory accuracy, therefore, this scope cannot comment on its effect. The number of repetitions of the speech materials across all studies ranged from 5 to 12.

Table 3. EMA papers included in this review recorded by author and date, country of origin, participant information, methods and metrics, speech materials and key findings.

Author & Date	Country of Origin & Language	Instrument	Participants (Age, Gender + Diagnosis)	Methods + Metrics	Speech Materials	Key Findings
Cheng et al. (2007a)	Australia Australian English	EMA	–48 children and adults TD Equal number of male/ females in each group (1)12 6–7 years (2) 12 8–11 years (3) 12 12–17 years (4) 12 adults 28–38 years	VI EMA coils connected to tongue tip, tongue blade and midline jaw, measuring tongue-jaw coordination Sentence repeated five times	/t/, /k/ Embedded in sentence 'A **t**arp covers a **c**ar' 240 data points for each consonant, 480 total	No significant effect of age for VI of tongue and jaw movement for /t/. Significant effect of age for VI of tongue and jaw movement for /k/, adults were less variable than all younger groups. The relationship between VI values for /k/ and age was linear.
Terband et al. (2011)	The Netherlands Dutch	EMA	–10 children with SSD (6–9 years) 5 subtype CAS 5 subtype phonological –6 age-matched TD children	STI EMA coils connected to tongue tip, lower lip and midline jaw, measuring tongue-jaw coordination	/s/, /p/ **S**pa, **P**as real word 5 or 12 second trials Participant will produce repetitions at self-regulated pace Number of data points not reported	A significant effect of group was found on the tongue tip trajectory between CAS and TD group where the CAS group had higher STI which indicates a higher articulatory variability. Tongue tip amplitude was significantly higher in variability for the Phonological group compared to CAS and TD. CAS group found to have significantly more amplitude variability of the lower lip compared to the TD group.

(*Continued*)

Table 3. (Continued).

Author & Date	Country of Origin & Language	Instrument	Participants (Age, Gender + Diagnosis)	Methods + Metrics	Speech Materials	Key Findings
Murdoch et al. (2012)	Australia Australian English	EMA	–48 children and adults TD Equal number of male/ females in each group (1)12 6–7 years (2) 12 8–11 years (3) 12 12–17 years (4) 12 adults 28–38 years	STI for Set 1 CoV of distance, duration, speed, acceleration and deceleration of consonants in Set 2 Set 1: sentences repeated 10 times Set 2: sentences repeated five times	Set 1: 'Tess told Dan to stay fit' 'Karl got a croaking frog' 'Buy Bobby a puppy' 30 sentence data points Set 2: /t/, /s/, /l/ , /k/, /p/ 'A **t**arp covers a **c**ar' 'Pa **s**aw a shark and a **l**ark' 'Buy Bobby a **p**uppy' 240 data points for each consonant	A significant linear effect of age on the general reduction of STI of the tongue tip, body and lip as age increases. Significantly greater variability (higher STI) observed in group (1) compared to groups (3) and (4). Significantly greater variability (higher STI) observed in group (2) compared to group (4). Articulatory distance, duration, speed, acceleration and deceleration of consonants were significantly less variable (lower CoV) in adults compared to the three child groups, but few significant differences were observed between groups for these metrics (1), (2) and (3). There was an overall trend of a reduction in variability on both temporal and spatial metrics.
Nip et al. (2017)	USA American English	EMA	–4 male children with spastic CP, (9–14 years) –4 TD age-matched male children (9–14 years)	Zero-lag correlations of tongue tip and jaw distance, duration and speed First repetition was compared to mean of the remaining reps Ten repetitions of sentence	'Dad told stories today' 40 sentence data points per group	Those with CP were significantly more variable (low zero-lag correlation) for both tongue tip and jaw when compared to their TD peers. Jaw movement had a significantly greater degree of stability (higher correlation) than tongue for both groups. No significant effect of age was found for either group.

Table 4. EPG papers included in this review recorded by author and date, country of origin, participant information, methods and metrics, speech materials and key findings.

Author & Date	Country of Origin & Language	Instrument	Participants (Age + Diagnosis)	Methods + Metrics	Speech Materials	Key Findings
Cheng et al. (2007b)	Australia Australian English	EPG	–48 children and adults TD Equal number of male/ females in each group (1)12 6–7 years (2) 12 8–9 years (3) 12 12–17 years (4) 12 adults 28–38 years	VI of palate contact Six words in CV and CVC structure repeated five times embedded in phrase	/t, l, s, k, kl, st/ 'A **t**arp covers a **c**ar' 'Pa **s**aw a shark and a **l**ark' 'A **cl**erk squeezes a **st**ar' 240 data points for each consonant	No significant effect for anterior consonants /t, l, s/ across age groups for VI. Significant effect on variability of /k/ across age groups, younger groups more variable (higher VI) than older, effect was linearly related. Group (1) was significantly more variable (higher VI) than group (3) and (4) for /k/.
Cheng et al. (2007)	Australia Australian English	EPG	–48 children and adults TD Equal number of male/ females in each group (1)12 6–7 years (2) 12 8–9 years (3) 12 12–17 years (4) 12 adults 28–38 years	CoV of palate contact Five words in CV and CVC structure repeated five times embedded in phrase	/t, l, s, k, kl/ 'A **t**arp covers a **c**ar' 'Pa **s**aw a shark and a **l**ark' 'A **cl**erk squeezes a star'	No difference in CoV for all segmental durations across age groups.
Timmins et al. (2009)	Scotland Standard Scottish English	EPG	–20 young people with Down's syndrome 8–19 years –8 TD children 4–8 years –8 TD adults Gender not reported	VI of palate contact Phrase repeated 10 times	/ / 'a **sh**eep' 360 data points for consonant	No significant difference in VI between DS and TD groups. Adults significantly less variable (lower VI) than TD and DS groups.

Table 5. UTI papers included in this review recorded by author and date, country of origin, participant information, methods and metrics, speech materials and key findings.

Author & Date	Country of Origin & Language	Instrument	Participants (Age + Diagnosis)	Methods + Metrics	Speech Materials	Key Findings
Zharkova et al. (2011)	Scotland Standard Scottish English	UTI- Stabilised	−10 TD children (6;2–9;9) −10 TD adults (27–46) Gender not reported	mNND of midsagittal tongue contour of consonant Phrase repeated 10 times	/ʃi/, /ʃu/, /ʃa/ In carrier phrase 'it's a __ Pam' 200 data points per vowel context	Significantly larger mNNDs in children compared to adults for all vowel contexts, demonstrating greater variability.
Zharkova et al. (2012)	Scotland Standard Scottish English	UTI- Stabilised	−same participant group as Zharkova et al. (2011)	mNND of midsagittal tongue contour of consonant Phrase repeated 10 times	/si/ /su/, /sa/ In carrier phrase 'it's a __Pam' 200 data points per vowel context	The children were significantly more variable (greater mNND) in lingual articulation of /s/ across tokens than adult speakers for all vowel contexts. A trend of greater variability in consonant of /si/ compared to /sa/ and /su/ in the children's group, however, not significant.
Zharkova et al. (2014)	Scotland Standard Scottish English	UTI – Stabalised	−15 TD preadolescents (10;0–12;4) 6 females 9 males −15 TD adults (18–58) 12 females 3 males	mNND of midsagittal tongue contour of consonant Phrase repeated six times	/si/, /sa/ /ʃi/, /ʃa/ In carrier phrase 'it's a __Pam' 360 data pointes per vowel context	Age had no significant effect on mNND for both /s/ and /ʃ/ despite the preadolescents having higher mNND values on average.
Zharkova et al. (2015)	Scotland Standard Scottish English	UTI- handheld and stabilised	−10 TD adolescents (13;0–13;11) 6 females 4 males	mNND of midsagittal tongue contour of consonant Each task was recorded twice with each participant, one with head stabilisation, the other without Each phrase repeated six times	/ /, /s/, /t/, /p/, /i/ , /a/ As CV syllables within carrier phrase 'It's a __ Pam' 120 data points per consonant	Handheld was more significantly variable (higher mNND); however, stabilised did show a degree of within speaker lingual variation of each consonant.

(*Continued*)

Table 5. (Continued).

Author & Date	Country of Origin & Language	Instrument	Participants (Age + Diagnosis)	Methods + Metrics	Speech Materials	Key Findings
Zharkova (2017)	Scotland Standard Scottish English	UTI- non stabilised	−10 TD children (5;5–5;11) Equal male and females −10 TD adolescents (13;0–13;11) 6 Females 4 Males	CoV for both Dorsum Excursion Index (DEI) and LOCa-I Five repetitions	/ta/, /ti/ In carrier phrase 'It's a __ Pam' 100 data points per vowel context	Significantly more token-to-token tongue shape variability observed in 5 years (higher CoV) compared to 13 years for both metrics. No effect on variability across vowels and age group.
Lenoci and Ricci (2018)	Italy Italian	UTI-stabilised	−4 children who stammer (8;2–12;4) −4 age matched TD children (8;1–12;4) Equal male and females in both groups	mNND Twelve repetitions	/da/, /ga/ In carrier phrase 'La gattina __ba salira' (The little cat __ba will go up) 96 data points per consonant	Stammer group showed significantly increased tongue shape variability (greater mNND) on fluent repeated items of both /da/ and /ga/.
Barbier et al. (2020)	Canada Canadian French	UTI-stabilised	−20 TD children (4;0–4;11) −10 TD adults (19–30-years) Gender not reported	mNND 8–10 repetitions of isolated vowels	/i/, /e/, /ε/, /a/, /u/ Produced in isolation	Children's tongue shapes were more variable (higher mNND) compared to adults for all vowels.
Lenoci et al. (2021)	Italy Italian	UTI-stabilised	−5 children with CAS (8;10–12;1) −5 TD children (9;3–12;5)	mNND Each phrase repeated eight times	/a/, /i/, /u/ In non-words: Adaba, Adiba and Aduba in '__ goes down' 80 data points for each vowel	Tongue shape variability found to be significantly higher in children with CAS. Some TD speakers had higher mNNDs on certain vowels compared to the children with CAS.

Electromagnetic Articulography

Table 3, which summarises the papers using EMA, shows a trend that children and adolescents show more articulatory variability than adults. Cheng et al. (2007a) and Murdoch et al. (2012) had the largest sample size of 48 children and adults and used both the variability index (VI) and spatiotemporal index (STI) to measure different aspects of speech motor control (see Table 3). For both metrics, a linear effect is observed on the reduction of variability as age increases in the sentences and the velar consonant /k/. No effect was found for the anterior consonant /t/. Whilst the younger groups are generally more variable than the older groups, few conclusions can be made when comparing ages 4–17 years using the VI and STI metrics.

In the Nip et al. (2017) study comparing children with cerebral palsy and typically developing children, no significant effect of age was found in the TD group. However, this study had a very limited sample size of four children aged 9–14 years. Terband et al. (2011) do not describe TD variability over time, however, they did detect articulatory variability in the TD group, which was significantly less than the groups with SSD of different origins.

Electropalatography

Table 4 shows that Cheng et al. (2007b) and Cheng et al. (2007) used the same participant sample and stimuli but utilised different metrics. They used the VI and CoV to identify variation in linguopalatal contact patterns respectfully Neither study observed a significant effect of age for the anterior consonants /t, s, l/. However, the findings pertaining to the variability index suggest that younger children had more variable production of /k/.

Timmins et al. (2009), also used the VI, specifically to look at the variability of the post-alveolar fricative/ʃ/ in children with and without Down syndrome. They reported that TD children aged 4–8 years were significantly less variable than the DS group, yet more significantly variable than the adult group.

Ultrasound Tongue Imaging

All but one of the UTI papers in Table 5 used mNND (see Table 5), to measure variability in lingual articulation. Zharkova et al. (2011) and Zharkova et al. (2012) directly compared single consonant mNNDs of children aged 6–9 years to adults and found that the children were significantly more variable than the adults for /s/ and /ʃ/ across different vowel contexts. However, Zharkova et al. (2014) found no significant effect on mNND between preadolescents and adults of the same consonants. Barbier et al. (2020) found a significant effect on variability and age for isolated vowels, with 4-year-olds being more variable compared to adult speakers.

Zharkova et al. (2015) report a degree of variability within adolescents' speech but did not compare their performance with older, or younger groups. In contrast, using the DEI and LOCa-I, Zharkova (2017) observed a degree of variability in the adolescent group. In addition, a comparison with children's performances on these metrics showed that adolescents in this study were significantly less variable than the children.

Discussion

This scoping review describes the current landscape of instrumental techniques used to investigate articulatory variability in TD children's speech. Understanding developmental change in variability is important for theories of the development of speech motor control and for understanding impaired speech motor control in children with SSD.

We were interested in how various instrumental techniques compare, and how speech motor control develops over time in TD children. Whilst we focused on only three instruments used to investigate lingual articulatory variability, these instruments are diverse in what they measure. While UTI/EPG analyses tend to compare single time point data during, e.g. gesture maxima, EMA analyses are often dynamic over longer speech domains. UTI and EPG were used to provide insights into the spatial variation when comparing multiple single time points, whereas EMA can capture variation in a variety of articulatory parameters, such as amplitude, duration, speed and velocity for repetitions of whole utterances using the STI measure. Depending on the placement of the coils, EMA can also measure different areas of the tongue (back and tip). However, this is also true for UTI as the ultrasound displays a large portion of the tongue's surface, and measurements can be made that focus on either localised areas or the whole surface. Although EPG measures tongue-palate contact, it cannot describe exactly which parts of the tongue are used when.

Given the specificity of what each instrument and measure documents, it is difficult to summarise the key findings of the studies included. However, we can observe a trend of decreasing variability over time as children develop their speech motor control into adult-like speech. Crucially, this variability appears to be lower for coronal articulations, than for dorsal articulations.

Consonants

An interesting observation that can be made is the distinction between the variability of the posterior consonant /k/ and the anterior consonants studied. Cheng et al. (2007a, 2007b), using EMA and EPG, found a linear relationship between age and variability for /k/, but no such effect for /t, s, l/ when using the VI. This seems to indicate that consonants which use the back, or body, of the tongue are more variable in production compared to consonants which primarily use the tongue tip/blade. One potential explanation for this finding is that the tongue tip contains a dense gathering of nerve endings, compared to posterior parts of the tongue (Mu & Sanders, 2010), creating an increase in tactile feedback, which may lead to more consistent tongue placement. Moreover, because the tongue is capable of high levels of differentiated articulation in the tip/blade, there is a greater number of English sounds produced at the front of the oral cavity compared to the back, meaning the articulatory gesture of anterior sounds requires greater precision to distinguish between them. However, when using the STI measure in their EMA study, Murdoch et al. (2012) found a linear effect of age on variability for sentences containing both anterior and posterior consonants, where there was a general reduction of variability as age increased. This could suggest that the STI may in fact be a more sensitive measure of articulatory variability compared to the VI. Cheng et al. (2007), which we presume used the same participant sample, found no significant effect using the coefficient of variation on EPG data.

When considering these papers, we see few statistically significant results from ages 6–17 years, yet all younger groups were significantly more variable for /k/ when compared to the adult group. This result supports the theory that articulatory refinement into adult-like speech continues well into adolescence (Schötz et al., 2013; Smith & Zelaznik, 2004; Walsh & Smith, 2002). However, when the mNND measure is used for UTI data, we do see significant differences in speech variability between children aged 5 and 13 years, where the younger group is more variable for the anterior consonant /t/. This may be due to the advantages of UTI, where the whole of the tongue's surface can be quantified, rather than just a flesh-point measure, as is the case with EMA. In other words, the area of the tongue that is active in creating the articulatory target might be less variable than the overall tongue shape.

When considering future research, to reduce barriers to incorporating research into clinical practice, the instrument(s) used should be carefully selected.

Clinical implications

The results of this review highlight the gaps in research that need to be addressed for clinicians to understand typical articulatory variability, compared to the disordered populations they work with. A comprehensive normative data set is needed to understand the threshold at which an increase in variability is indicative of speech disorder. Research of this type is currently underway in Scotland (Variability in Child Speech, 2023.)

Limitations

The literature screening process was carried out by the first author only. The validity of this scope would have been strengthened by additional screening (Peters et al., 2015). When conducting the search, we used English search terms only, which may have missed studies published in languages other than English. The search criteria for this review were narrow and did not include studies focused on adult or clinical populations. Lastly, this review included papers that used instrumental techniques that recorded tongue movement only, and we limit our review to biomechanical variability only, choosing to exclude findings on the development of coarticulation. A review incorporating other techniques such as VICON and acoustic studies and incorporating the findings of the many studies focused on coarticulation would provide a broader understanding of articulatory variability and the development of speech motor control in the TD population.

Conclusions and recommendations

This review answered which methodologies and metrics have been used in the study of lingual articulatory variability in typically developing children. EMA, EPG and UTI have been utilised to measure a variety of spatial and temporal articulatory features of speech. However, variation in participant samples and recording and analysis methods inevitably make it difficult to synthesise findings. The studies included also encompass a limited set of languages.

The current review suggests a reduction of variability from ages 5–18 years, which supports the idea of a protracted motor speech development period, where children and adolescents are refining and adjusting articulatory movements of some consonants. We can see from the results of the included studies that when using a variety of methods and metrics, children are more articulatorily variable in their lingual movements than adults, but what is still unclear is how variable children of different ages are and what the normal range of variability is for each age range. To understand this, a comprehensive longitudinal study, using a technique easily incorporated into clinical practice is necessary. Further research is also needed into theories of motor speech development and how variability and coarticulation interact in typical speech development in order to fully understand the trajectory typical children take.

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Appendix. List of papers included in review

Electromagnetic Articulography:

(1) Cheng et al. (2007a). Physiologic development of tongue-jaw coordination from childhood to adulthood. *Journal of Speech, Language & Hearing Research*, *50*(2), 352–360. https://doi.org/10.1044/1092-4388(2007/025)
(2) Terband et al. (2011). Stability and composition of functional synergies for speech movements in children with developmental speech disorders. *Journal of Communication Disorders*, *44*(1), 59–74. https://doi.org/10.1016/J.JCOMDIS.2010.07.003
(3) Murdoch et al. (2012). Developmental changes in the variability of tongue and lip movements during speech from childhood to adulthood: An EMA study. *Clinical Linguistics & Phonetics*, *26*(3), 216–231. https://doi.org/10.3109/02699206.2011.604459
(4) Nip et al. (2017). Initial Observations of Lingual Movement Characteristics of Children With Cerebral Palsy. *Journal of Speech, Language & Hearing Research*, *60*, 1780–1790. https://doi.org/10.1044/2017_JSLHR-S-16-0239

Electropalatography papers:

(1) Cheng et al. (2007b). Electropalatographic Assessment of Tongue-to-Palate Contact Patterns and Variability in Children, Adolescents, and Adults. *Journal of Speech, Language & Hearing Research*, *50*(2), 375–392. https://doi.org/10.1044/1092-4388(2007/027)
(2) Cheng et al. (2007). Temporal Features of Articulation from Childhood to Adolescence: An Electropalatographic Investigation. *Clinical Linguistics & Phonetics*, *21*(6), 481–499. https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ763967&authtype=shib&site=ehost-live&authtype=ip,shib&custid=ns075038

(3) Timmins et al. (2009). A perceptual and electropalatographic study of/ʃ/in young people with Down's syndrome. *Clinical Linguistics & Phonetics*, *23*(12), 911–925. https://doi.org/10.3109/02699200903141271

Ultrasound Tongue Imaging papers:

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