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Interactivity in prosodic representations in children*

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ABSTRACT

The aim of this study was to determine, using speech error and articulatory analyses, whether the binary distinction between iambs and trochees should be extended to include additional prosodic subcategories. Adults, children who are normally developing, and children with specific language impairment (SLI) participated. Children with SLI were included because they exhibit prosodic and motor deficits. Children, especially those with SLI, showed the expected increase in omission errors in weak initial syllables. Movement patterning analyses revealed that speakers produced differentiated articulatory templates beyond the broad categories of iamb and trochee. Finally, weak–weak prosodic sequences that crossed word boundaries showed increased articulatory variability when compared with strong–weak alternations. The binary distinction between iamb and trochee may be insufficient, with additional systematic prosodic subcategories evident, even in young children with SLI. Findings support increased interactivity in language processing.

INTRODUCTION

Kinematic evidence has the potential to contribute to an account of prosodic development and, more broadly, of interactivity in language processing. For this study, our aim was to assess whether children, both those with typical language and with specific language impairment (SLI), and adults implement distinct prosodic patterns within words that are embedded in different linguistic contexts. Two experimental analyses were planned. In the first, we used standard transcription measures to assess whether older children who are normally developing (ND) or have SLI produce the

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expected omission and segmental substitution errors in vulnerable prosodic environments. In the second analysis, we obtained direct articulatory kinematic measures to evaluate whether distinct prosodic patterns emerge in different grammatical and segmental contexts. Together, transcription and kinematic approaches can inform our understanding of the representation and interactivity of prosodic categories.

In metrical stress theory it is hypothesized that there are two basic rhythmic sequences, iambic (weak–strong) and trochaic (strong–weak; e.g. Hayes, 1995). Rhythmic sequences are organized into units of strong and adjacent weak syllables, termed 'metrical feet' (see Gerken & McGregor, 1998, for a review). English allows trochaic metrical feet, which consist of a strong syllable followed by a weak syllable. Strong syllables also may stand alone. Iambic feet, defined as weak followed by strong syllables, are not considered well-formed in English. Therefore, weak syllables that precede strong are referred to as unfooted. Unfooted syllables are particularly vulnerable to error in children acquiring English (Gerken & McGregor, 1998).

While most accounts rely on this binary distinction between iambs and trochees, it may be that additional subtypes of rhythmic sequences, or feet, can be identified as linguistic demands change over the course of development. Prosodic aspects of output may be influenced by other domains of linguistic processing, such as segmental, lexical, and morphological. For example, affixes ''bearing weak stress'' are particularly sensitive to prosodic demands (Hayes, 1995: 32). Segmental complexity (Gerken & Ohala, 2000; Zamuner & Gerken, 1998) and lexical frequency (Boyle & Gerken, 1997) may also influence how weak syllables are instantiated. Because multiple dimensions of language, including lexical, morphosyntactic, and segmental components, are likely to develop more slowly in children with SLI, this population provides an ideal test case for investigating interactions across the prosodic hierarchy.

In the present study, we are interested in whether the prosodic organization of iambic and trochaic words is influenced by the language context in which they occur. We first replicate and extend earlier transcription-based findings to assess whether unfooted weak syllables are especially prone to production errors in older children, aged four to six years. Because these children are relatively accurate, perceptually based phonetic transcription may be limited in revealing whether an inventory of foot types can be identified that extend beyond the broad categories of iamb and trochee. With this limitation in mind, we then turn to an analysis of speech motor kinematics to index whether the rhythmic structure of movement patterning varies systematically when iambic and trochaic words are produced in different linguistic contexts. We ask whether additional systematic rhythmic distinctions can be made that include more nuanced

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subcategories than iambic and trochaic. For example, within the iambic foot structure, it may be that weak syllables associated with grammatical inflections are produced differently from weak syllables of content words. More fine-grained articulatory kinematic approaches have the potential to determine whether the broad categories of iamb and trochee are sufficient or whether additional rhythmic stress patterns can be identified.

Finally, again relying on kinematic evidence, we evaluate whether non-alternating stress sequences (i.e. weak–weak; WW) are produced with more movement variability than alternating (i.e. SW). The multiple levels of analysis should provide insights regarding the nature of the prosodic deficit in SLI and inform whether the existing binary iambic and trochaic distinction, suggested by perceptually based error analysis, should be extended to include additional prosodic subcategories.

Review of developmental account

Even infants mark stress, as indicated by increases in duration, intensity, and fundamental frequency in stressed compared with unstressed syllables (Davis, MacNeilage, Matyear & Powell, 2000; Vihman, DePaolis & Davis, 1998). A trochaic bias is not revealed, since both iambic and trochaic sequences are produced with appropriate stress marking (Davis *et al.*, 2000). However, once toddlers begin to produce words, omission errors provide substantial evidence that trochaic sequences are less vulnerable to error than iambic.

In English, children's prosodic errors are often accounted for by the postulation of a trochaic production constraint, in which syllables are retained that can be parsed into binary feet which fit a trochaic template (Demuth, 2003; Echols, 1993; Gerken, 1994; 1996). On this account, children are sensitive to the structure of the majority of English words and thus attempt to produce well-formed (i.e. S or SW) syllable sequences, omitting syllables that are inconsistent with this structure or are unfooted. For example, for young children an iambic word such as *balloon* is frequently produced as [lun], whereas a trochaic word such as *baby* is unlikely to include such a weak syllable omission error.

Omission errors occur variably. Investigators have attempted to understand the nature of this variability, hypothesizing that other linguistic factors may condition the likelihood that an omission error will occur. For example, Boyle and Gerken (1997) demonstrated that children are more likely to omit unfooted weak syllables from function words in unfamiliar than familiar contexts.

It is also important to consider that prosodic effects not only occur within a word, but also cross word boundaries and thus influence grammatical inflections. For example, children will form a trochaic foot across word

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boundaries, producing fewer omissions of the functor *the* in *Tom pushed the bear* compared to in *Tom pushes the bear* (Gerken, 1996). In the first case *pushed the* forms a trochaic foot, even though it crosses from a verb to the following noun phrase. The preference for a well-formed prosodic foot crosses word and phrase boundaries with prosodic constraints overriding syntactic ones. The same trochaic template may influence the production of content and of function words. Finally, it has been suggested that segmental factors may also interact with the frequency of prosodically conditioned errors (Gerken & Ohala, 2000; Zamuner & Gerken, 1998).

In sum, unstressed syllables in iambic feet are especially vulnerable. While it is established that multiple linguistic factors contribute to the likelihood of prosodically motivated errors, it remains unknown whether there are additional prosodic categories beyond those associated with iambs and trochees. It may be that the broad and binary categories of iamb and trochee are simply too coarse and that more refined subcategorization of prosodic foot structure may provide a stronger explanatory account of children's and adults speech production.

How does motor evidence change the problem space?

Iambic and trochaic prosodic forms have recognizable signatures that appear in the patterning of articulatory movement (Goffman, 1999; 2004). The use of kinematic evidence allows for a more detailed analysis of systematic and recognizable patterns that may emerge across distinct prosodic categories (Grigos & Patel, 2007). One possibility is that the only differentiable categories are iambs and trochees. Standard models of speech production, such as Levelt's (Levelt 1989; Levelt, Roelofs & Meyer, 1999), propose discrete levels of processing for form encoding, which includes prosodification and syllabification, and for phonetic encoding. In this view, morphemic processing occurs prior to syllabification and the application of metrical structure. This is a hierarchical model, in which phonological structure is then fed into phonetic encoding and articulation. Articulation relies heavily on a mental syllabary, which is a catalog of highly frequent syllables (Cholin, Schiller & Levelt, 2004). Systematic changes in the structure of syllables that are conditioned by lexical, morphosyntactic, or segmental status would likely not be predicted by this account.

It is also possible that even highly frequent syllables vary systematically as a function of other language variables, such as lexical and morphosyntactic context. In this alternate view, there is thought to be interactivity among processing levels (Rapp & Goldrick, 2006). Empirical findings support a lexical–articulatory interaction. For example, Baese-Berk and Goldrick (2009) found that voice onset time (VOT) varied as a function of neighborhood density. McMillan, Corley, and Lickley (2009) asked

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participants to produce real word and nonword pairs. They observed increased substitution errors when word pairs included real word competitors. Further, more kinematic variability occurred in nonwords than in real words. These investigators argue that lexical and articulatory levels have more direct interaction than that proposed by discrete models. Direct recordings of articulatory movement change the problem space in that it becomes possible to examine how prosodic structure interacts with other aspects of language; there may be more reticulated prosodic subcategories than iambic and trochaic. We assess whether, as language demands change, distinct movement patterning is observed even within iambic and trochaic categories.

Patterning of prosodic templates. Syllable stress is defined as the ''linguistic manifestation of rhythmic structure'' (Hayes, 1995: 1). In the kinematic domain, correlates of stress are amplitude and duration. Fundamental frequency is an additional acoustic correlate. In speech, the most direct measure of rhythmicity is at the level of articulation (Goffman, 1999; 2004; MacNeilage & Davis, 2000), where oral movements are relatively small and short in weak compared to strong syllables (Goffman, 1999; 2004; Goffman, Heisler & Chakraborty, 2006).

Kinematic evidence may be used to assess the prosodic template. Our previous work has focused on bisyllabic nonce nouns, and has shown that the prosodic template is distinct for iambic and trochaic words (Goffman, 1999; 2004; Goffman *et al*., 2006; Goffman & Malin, 1999). Children and adults produce weak syllables in iambic content words differently from those that occur in trochaic content words. Specifically, weak syllables in iambs are produced with movements that are smaller and shorter than the strong syllable that follows. In contrast, for children, the highly frequent and early developing trochaic word is produced with movements that are similar in amplitude and duration for weak and strong syllables. Adults also show asymmetries between iambs and trochees, in that trochees are produced with strong and weak syllables that are relatively equal in weight (i.e. similar in amplitude and duration), whereas iambs increase quantitative contrasts between weak and strong syllables (Goffman, 1999; Goffman *et al*, 2006; Hayes, 1995; Prince, 1990). Distinct rhythmic articulatory templates are observed for iambic and trochaic words, even when considering the weak syllable in isolation.

Very little is known about whether distinct prosodic templates are produced as a function of language context. In one study, again using nonce words (in order to control for segmental content), adults were observed to produce distinct articulatory movement templates in content versus function words (Goffman, 2004). Speakers were introduced to a character from another planet named Sam. They were told *Sam's from outer space*. *He's not a boy*. *He's not a dog*. *He's a bab*. They then produced the sentence

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Sam's a bab, which includes an article + noun construction. In another condition, the same speakers were told *Sam has many funny toys. This toy's called an [ə'baeb]*. In this condition, the same phonetic form now comprised a WS content word, and participants produced the phrase *Sam's [ə'baeb]*. Adults showed sensitivity to the morphosyntactic distinction, producing larger amplitude movements for the weak syllable in the article than the content word condition. Children, however, included the same articulatory rhythmic structure across the two morphosyntactic conditions, and produced similarly small movements in weak syllables associated with content and function words. Children invoked a single collapsed prosodic category for the production of iambs irrespective of grammatical context. In the present study, we assess whether the patterning of the spatial and temporal correlates of stress reveal prosodic templates beyond iambs and trochees within a lexical item.

Variability of prosodic sequences. Kinematic evidence may also reveal the ease with which a speaker produces a prosodic target. The ability to produce the same articulatory movement pattern on each rendition of a given target provides a measure of the stability of a motor representation. Variability is thought to register reorganization in learning and to be an index of flexibility, or plasticity (Thelen & Smith, 1994). There are multiple sources of variability. Often increased variability is an index of immaturity, with younger children producing more variable movements than older children and adults (e.g. Smith & Goffman, 1998; Smith & Zelaznik, 2004). Children with SLI show more variability than their age-matched peers (Goffman, 1999; 2004). Alternatively, decreased variability may reveal that a speaker has some covert awareness that expressing a particular distinction is important. It may be that iambic nouns require more precision than trochaic nouns. However, often unfooted syllables are free-standing grammatical morphemes, such as the article *a* in the sentence *Spot's a dog*. In the present study, we ask about shifts in movement variability in prosodic contrasts that extend across word boundaries.

Within-individual effects have been observed in articulatory variability. Children are more variable in their production of a phrase embedded in a longer and more complex sentence frame than when the same phrase is produced in isolation (Maner, Smith & Grayson, 2000). In addition, words are produced with more variability when they have no meaning than they are when a visual referent has been introduced in a learning task (Heisler, Goffman & Younger, 2010). Thus, shifts in variability may reflect changes in the complexity of the learning task or environment.

With this background, it may be reasoned that a large degree of variability in the production of multiple renditions of an iambic or trochaic template reflects increased difficulty. Counter-intuitively, such speech motor patterning variability is higher in more frequently occurring trochaic

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words than in less frequent and later developing iambic words (Goffman, 1999; Goffman *et al.*, 2006). One possible explanation is that, for English, due to the high frequency and early occurrence of trochaic nouns, children rely on a basic unmodulated rhythmic sequence for the production of these words. Iambs require that speakers invoke a more specified, precise movement pattern in order to mark their contrast to the default trochaic pattern. In other languages it is possible that such a default unmodulated rhythmic structure would apply to other prosodic structures (Demuth, 2001; 2003; Vihman *et al.*, 1998). Children learning English produce trochaic nouns with movements that are relatively variable compared with iambic sequences. It is not known whether less canonical stress alternations that cross word boundaries (e.g. an article + content word that together form an iambic stress pattern) also show the increased precision that has been observed within an iambic word.

Hypotheses of the current study

The overarching goal of the present study is to assess whether the phonetic and articulatory components of prosodic structure vary as a function of higher-order phonological and morphosyntactic factors, thus revealing interactive processing. The specific hypotheses are:

(1) Older children will produce increased omission and segmental substitution errors in iambic words. These errors will be especially predominant in children with SLI.
(2) The articulatory patterning of prosodic templates will reveal differentiable subcategories that extend beyond the broad classes of iambic and trochaic stress patterns. Specifically, morphological and segmental factors will systematically influence the production of weak and strong syllables within the iambic and trochaic categories.
(3) Articulatory movement variability will decrease in alternating (footed; SWSW) compared with non-alternating (unfooted; SWWS) prosodic sequences that cross word boundaries.

METHODS AND RESULTS

General methods

Participants. Three groups of individuals participated in this study, including fourteen adults (*ME* = 20 years, *SD* = 1·5, range = 18–23), seventeen four-year-old children who were ND (*ME* = 4;7 (years;months), *SD* = 0;3, range = 4;1–4;11), and fourteen four- to six-year-old children diagnosed with SLI (*ME* = 5;2, *SD* = 0;7, range = 4;3–6;5). Because it was a goal of this study to investigate children with ND independently of those with

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SLI, this group was from a narrower age range, and included only four-year-olds. Different subgroups of participants were included across analyses, for reasons that will be explained in the context of each analysis.

The adults reported unremarkable developmental, medical, and speech, language, and hearing histories. Both groups of children, ND and SLI, showed non-verbal cognitive skills within the range of normal as measured by the *Columbia Mental Maturity Scale* (Burgemeister, Blum & Lorge, 1972). In addition, all children demonstrated structural and functional oral motor skills within expected levels, as measured by the *Clinical Assessment of Oropharyngeal Motor Development* (Robbins & Klee, 1987). Auditory function was normal for all participants, as indicated by responses to pure tones presented bilaterally at 20 dB at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz.

As required by the diagnostic category (Leonard, 1998), the children with SLI all demonstrated language skills at least one standard deviation below the mean on the *Structured Photographic Expressive Language Test* (Dawson & Stout, 2003) and/or the *Reynell Developmental Language Scales*-US edition (Reynell & Gruber, 1990). The children who were ND all showed language skills within the normal range according to the *Reynell Developmental Language Scales*-US edition (Reynell & Gruber, 1990).

Procedures and stimuli. Children and adults participated in one 20- to 30-minute experimental session. Children were seated in a wooden Rifton chair that was designed for individuals with cerebral palsy and includes an adjustable headrest and a play tray. Adults were seated on a stable wooden chair. For the kinematic recording, all speakers faced the Optotrak camera during data collection trials and were able to move naturally while speaking.

The target trochaic (i.e. *baby*) and iambic (i.e. *baboon*) words were embedded in two different sentence frames. These differed in several ways, most critically in that in one the target iambic or trochaic noun was preceded by a free-standing function word that was a vowel (*Em's a* ____). The other sentence frame included a content word + bound morpheme (*Emma's* ____) and a coda. The target sentences were:

(a) Em's a baby (SWSW, preceded by a free-standing function word and a final vowel); [VC.CV][CV.CV]. denotes syllabification and [] foot structure)
(b) Emma's baby (SWSW, preceded by a content word and a coda); [VC.CVC.][CV.CV]
(c) Em's a baboon (SWWS, free-standing function word, final vowel); [VC.CV.]CV.[CVC]
(d) Emma's baboon (SWWS, content word, coda); [VC.CVC.]CV.[CVC]

For recording lip and jaw kinematics, it is essential that the target productions include labial consonants. The use of real rather than nonce words

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leads to some trade-offs. The word *baboon* is less frequently occurring than the word *baby*. The stimuli were all modeled and, as will be apparent in the data analyses, these speakers produced *baboon* as an iamb. However, the reduced frequency of occurrence of the iambic compared with the trochaic target word needs to be accounted for in the interpretation of the results. Sentences were paired with a picture referent (e.g. a baboon wearing a diaper and holding a baby bottle, for *Em's a baby*) and were presented using PowerPoint. Utterances were presented randomly within a block with no more than three of the same sentence produced successively. Fifteen imitated productions of each sentence were elicited, with the first ten consecutive fluent sentences selected for analysis. Imitative paradigms are frequently used in studies assessing stress production in young children (Gerken, 1994; 1996; Schwartz & Goffman, 1995) and children are thought to integrate their own production patterns into imitations of prosodic contrasts. All of the experimental groups received the same input.

Excluded data. Sessions were observed on videotape and coded by two graduate students with experience transcribing child speech. Utterances that either judge coded as containing disfluencies (i.e. repetitions, prolongations, or long pauses) or, for kinematic analyses, extreme head movement (e.g. moving out of camera range) were excluded.

Descriptive analysis of transcribed error patterns

The purpose of this analysis was to verify that the target utterances would pattern as predicted in the standard transcription-based analysis. An increased number of omission and substitution errors were predicted in unfooted weak syllables, especially for children with SLI.

Participants. A subset of child participants were included in this verification of the standard transcription-based errors, including twelve children with SLI and twelve of their ND peers. All were randomly selected from the larger pool.

Data recording and transcription. For phonetic transcription, high quality audio-recordings of experimental sessions were collected using a Sony DAT recorder (DTC-59ES) and a Crown PZM-180 microphone. Using the DAT tapes, tokens were phonetically transcribed by two graduate student judges trained in the phonetic transcription of children's speech. Standard broad IPA procedures were used for the transcription of segments. Because the target syllables were phonetically identical across prosodic and syntactic conditions, only the [bV] syllables (i.e. [beI] for *baby* in the SWSW and [bə] for *baboon* in the SWWS sequences) were included. Three types of error analyses were completed, including standard measures (expressed in proportions) of: (1) weak syllable omissions; (2) consonant omissions (e.g. [ə] for [bə]); (3) consonant substitutions. Inter-judge reliability values were

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TABLE 1. *Individual data: Proportions of syllable and consonant omissions in SWWS sequences*

Syllable omissions				Consonant omissions			
ND-4-yr		SLI		ND-4-yr		SLI	
Emma's	Em's a	Emma's	Em's a	Emma's	Em's a	Emma's	Em's a
0·21	0·15	0·41	0·38	0·00	0·00	0·59	0·00
0·00	0·75	0·00	0·57	0·00	0·00	0·36	0·29
0·00	0·13	0·00	0·00	1·00	0·00	0·00	0·00
0·00	0·00	0·00	0·93	0·00	0·00	0·93	0·00
0·00	0·00	0·00	0·65	0·00	0·00	1·00	0·00
0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
0·00	0·00	0·00	0·14	0·00	0·00	0·47	0·00
0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
0·00	0·00	0·00	1·00	0·00	0·00	1·00	0·00
0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
0·00	0·00	0·13	0·20	0·00	0·00	0·40	0·00
0·00	0·00	0·00	0·93	0·00	0·00	0·20	0·00

obtained for a randomly selected four children with SLI and one who was ND. Inter-judge agreement was minimally 95 percent for all five children.

Analyses. Because of the minimal errors, especially in the SWSW sequence, only descriptive results are included.

SYLLABLE OMISSIONS: In the canonical SWSW sequence, only one omission error occurred (in the production of a function word in the sentence *Em's a baby* by an ND four-year-old) across all twenty-four speakers. Syllables in this SWSW prosodic structure were not prone to omission and thus were not subjected to further analysis.

For the SWWS sequence, there were again few syllable omissions in the initial weak syllable (SWWS), which was associated with the content word *Emma* or the article *a*. Two children who were ND omitted these weak syllables. This small number of omissions was not surprising because this weak syllable could foot with the preceding strong syllable.

The second weak syllable in the sequence (SWWS), however, included numerous omission errors. These results are reported descriptively in Table 1. Due to the large number of zeros, statistical results are not reported. In the ND group, three of the twelve children variably omitted the initial weak syllable in the content word *baboon*. Eight of the twelve children with SLI showed similar omission errors. As shown in Table 1, there were more syllable omissions in the syllable [bə] in the frame *Em's a baboon* than in *Emma's baboon*, especially for children with SLI.

CONSONANT OMISSIONS: Only the initial syllables in the words *baby* and *baboon* could be subjected to consonant omission analysis (e.g. the

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production of [bə] as [ə], with retention of the vowel to mark the syllable), since the preceding weak syllable contained a single vowel. There were no consonant omission errors for any child for the word *baby* in the SWSW sequence. However, there were consonant omission errors for the word *baboon* in the SWWS sequence. One child who was ND produced the syllable [bə] as [ə], and eight children with SLI showed this error pattern. As shown in Table 1, children with SLI produced more consonant omissions than those who were ND. In contrast to the analysis of syllable omissions, an increased number of consonant omission errors were observed in the frame *Emma's baboon* as opposed to *Em's a baboon*. Once again, the effect was observed in the children with SLI, but not their ND peers.

SEGMENTAL ERRORS: Only one child with SLI produced a segmental error for the word *baby* in the SWSW sequence. Three children who were ND and seven children with SLI produced other segmental substitution errors in their production of the syllable [bə] in the word *baboon* (e.g. [kəbun] and [dəbum] for *baboon*). Unlike omission errors, substitutions did not appear to pattern differently across linguistic contexts.

SUMMARY OF SEGMENTAL ANALYSIS: It was expected that difficulties with weak initial (i.e. unfooted) syllables that have been observed in studies of younger children would also be present in these older children, particularly those diagnosed with SLI. This was indeed the case, with an increased number of omission errors occurring in the [bə] syllable in *baboon* compared with the [beI] syllable in *baby*. Other types of errors also were observed, including consonant omission and other weakening errors. Omission errors patterned differently across linguistic contexts. However, substitution errors were similarly distributed across contexts.

Kinematic analyses

The kinematic analysis was the primary focus of this study; from this analysis it could be determined whether children employ differentiable movement templates within iambic and trochaic categories and whether articulatory variability changes as a function of the complexity of the rhythmic alternation.

Participants. Because omissions did not occur in productions of the trochaic word *baby*, all fourteen adults, seventeen children who were ND, and fourteen children with SLI were included in the analyses of trochees. However, in the more critical iambic condition, because of the frequent occurrence of syllable omissions (especially for the children with SLI), the numbers were reduced for the child participants. In all, fourteen adults, thirteen children who were ND, and six who were SLI were included in the kinematic analyses of iambs.

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Data recording and extraction. Kinematic data were collected using the Optotrak, a system designed for recording human movement (Northern Digital). The tracking error of the Optotrak is less than 0·1 mm. Small (6 mm in diameter), flat light emitting diodes (IREDs) were attached at midline, partially overlying the vermilion zone of the upper and lower lips (only lower lip/jaw movements will be reported here). To correct for head movement, a third IRED was placed on the forehead. Kinematic data were collected at a sampling rate of 250 samples/second. A synchronous acoustic signal, sampled at 16,000 Hz, was also obtained. Analyses were performed using the Matlab signal processing program (MathWorks, 1993). Lower lip motion was corrected for head movement using a three-dimensional subtraction technique, and displacement data were low-pass filtered (10 Hz cut-off) prior to computation of velocity (see Goffman, 1999; Goffman & Smith, 1999; Smith, Goffman, Zelaznik, Ying & McGillem, 1995). Video-recordings were obtained to code for extreme head movement and speech errors such as disfluencies.

Kinematic records were collected in 45-second trials, during which children produced multiple sentences. The target utterances were selected because they included labial closure at the onset of the weak syllable/article (i.e. the [m] in *Em's a* or *Emma's*) and the onset and offset of the initial syllable in the following word (i.e. [bəb] in *baboon* and [beIb] in *baby*). As illustrated in Figure 1, movement onsets and offsets associated with lip closure were initially selected by visual inspection of the displacement record for local minima. An algorithm then determined the minimum value, corresponding to the experimenter-selected point. Selections of kinematic records were confirmed by playing back the synchronized acoustic signal.

Movement patterning. The rhythmic structure of individual syllables was assessed using point measures of movement amplitude and duration. Figure 2 shows how amplitude and duration measures of individual syllables were obtained from the initial syllables of the words *baby* and *baboon*. These amplitude and duration values could be compared across the two sentence frames *Em's a* ___ and *Emma's* ___ to assess the influence of linguistic context on the rhythmic structure of the initial syllables in iambic and trochaic words.

Movement variability. The spatiotemporal index (STI; Smith *et al*., 1995) was used to assess changes in variability across conditions and groups. As shown in Figure 3, the WS or WW sequence associated with the weak syllable that preceded the target word and the first syllable of *baboon* or *baby* was analyzed (e.g. in *Em's a baby*, *a bab* was extracted). The analytic purpose of the STI is to quantify the stability of underlying movement patterns when absolute differences in duration (e.g. rate) and amplitude (e.g. loudness) are eliminated. As illustrated in the middle panels of Figure 3, movement trajectories corresponding to the entire sequence were

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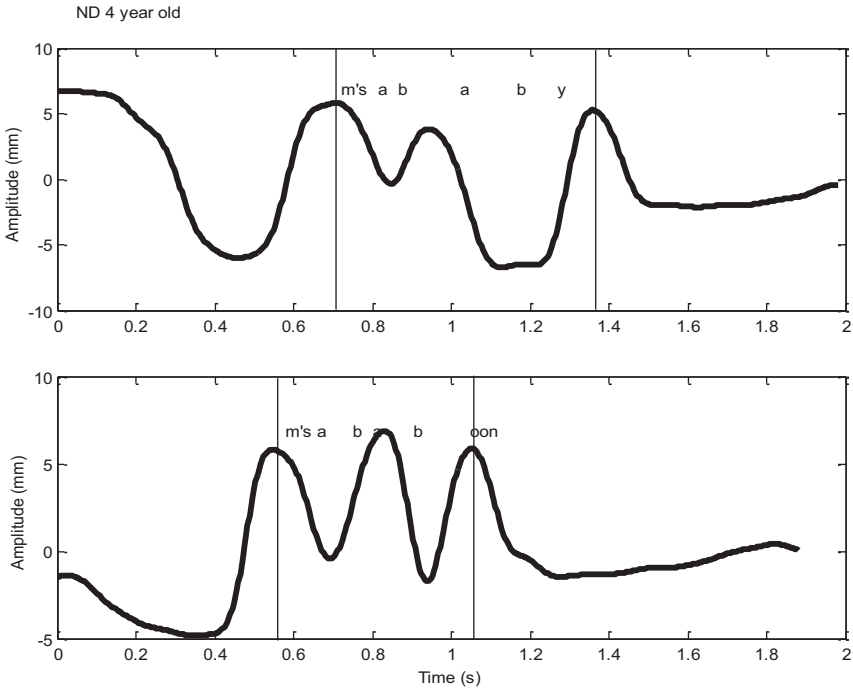


Fig. 1. Examples of extracted movement sequences from a four-year-old ND child producing the target sentences *Em's a baby* (top panel) and *Em's a baboon* (bottom panel). Movements were extracted, beginning with the lip closure for the [m] in *Em's* and ending with the second [b] in *baboon* or *baby*. The vertical lines show the WS or WW sequence used in the STI analysis.

initially linearly amplitude- and time-normalized. Amplitude-normalization was accomplished by subtracting the mean and dividing by the standard deviation of each displacement record. For time-normalization, a spline function (MathWorks, 1993) was used to interpolate each displacement record onto a time base of 1000 points (for a detailed description of this analysis, see Smith *et al.*, 1995; Smith, Johnson, McGillem & Goffman, 2000). Following normalization, as shown in the bottom panels of Figure 3, standard deviations were computed at 2 percent intervals across all of the time- and amplitude-normalized displacement records. The STI is the sum of these fifty standard deviations. A higher STI value indicates increased variability. Lower lip and jaw movement directly index the oscillatory frame used for the production of different syllable shapes (MacNeilage & Davis, 2000).

Analysis. For all analyses, a mixed ANOVA was performed, with group (ADULT, ND, SLI) as the between-subjects factor. In the patterning

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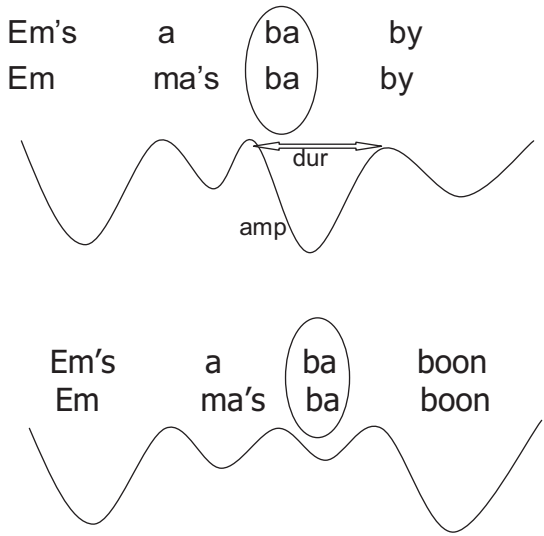


Fig. 2. Illustration of the method for assessing the amplitude and duration of the syllable [bVb]. As an example, the [beIb] in *baby* could be compared across the two morphosyntactic contexts.

analysis, the iambic (*baboon*) and trochaic (*baby*) words were analyzed separately. This was because opening movements associated with the initial weak [bəb] in *baboon* are inherently smaller and shorter than those associated with the initial strong [beIb] in *baby*. The within-subjects factor was linguistic context.

In the variability analysis, the between-subjects factor was again group (ND, SLI, ADULT). The within-subject comparisons were for the two medial syllables in the SWSW (i.e. well-formed alternation) vs. SWWS (i.e. poorly formed alternation containing an unfooted syllable) sequence and for linguistic context. For all analyses, post-hoc testing was completed using the Tukey HSD procedure, with a 0·05 significance level.

Results of kinematic analyses

Movement patterning. In this analysis it was asked whether children (ND or SLI) and adults produce more differentiated rhythmic structures within a given word than the binary iambic and trochaic categories.

The amplitude and duration of movement associated with the initial syllable in *baby* (illustrated in Figure 2) provided a direct comparison of linguistic effects on prosodic structure, since these forms were phonetically

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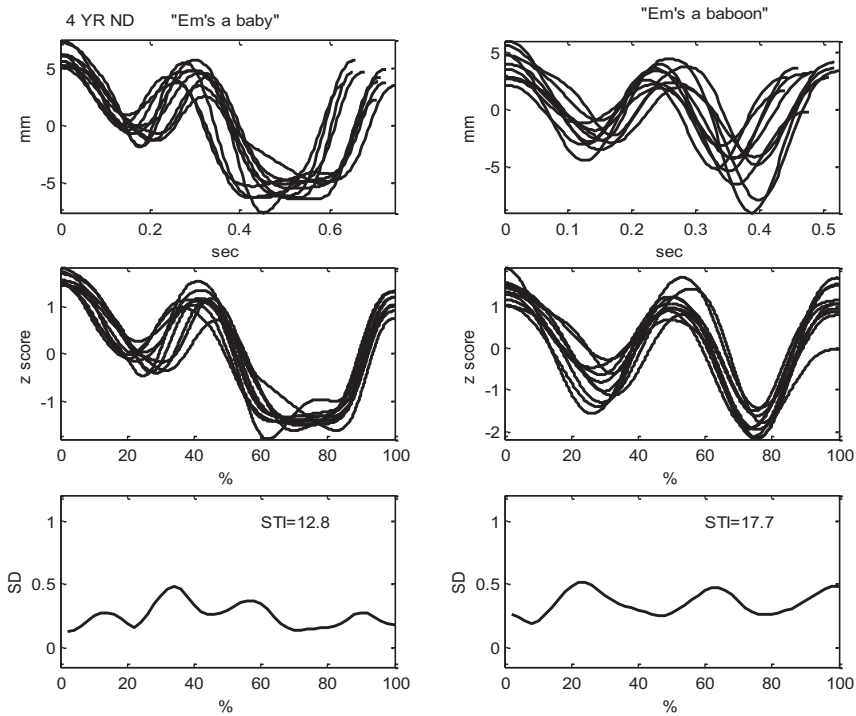


Fig. 3. Example of the spatiotemporal index (STI) for a four-year-old ND child producing the sentences *Em's a baby* and *Em's a baboon*. These records were extracted as shown in Figure 1. For each set of plots, the top panels illustrate the original, non-normalized records, the middle panels the same records, now time- and amplitude-normalized, and the bottom panels the spatiotemporal index (STI).

identical across the two conditions. As shown in Figure 4, for amplitude, there was no effect of group ($F(2, 40) = 0{\cdot}09$, $p = 0{\cdot}91$). There was an influence of linguistic context ($F(1, 40) = 22{\cdot}11$, $p < 0{\cdot}0001$), with movement amplitudes in the *Emma's baby* context larger than those in the *Em's a baby* context. All three groups showed this effect, as indicated by no group*linguistic context interaction ($F(2, 40) = 0{\cdot}40$, $p = 0{\cdot}67$).

Duration for the syllable [beI] showed a group effect ($F(2, 40) = 36{\cdot}69$, $p < 0{\cdot}0001$) (see Figure 5). Post-hoc testing revealed that adults produced shorter movement durations than both groups of children. There were no effects of linguistic context ($F(1, 40) = 0{\cdot}21$, $p = 0{\cdot}65$) on syllable duration.

For the amplitude of the initial weak syllable in *baboon* in the sentences *Em's a baboon* and *Emma's baboon*, there was an effect of group ($F(2, 30) = 5{\cdot}06$, $p = 0{\cdot}01$). As illustrated in Figure 4, children who were ND

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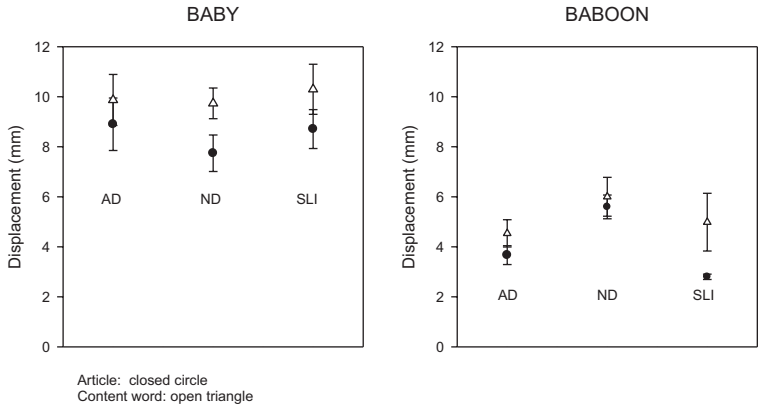


Fig. 4. Amplitude (in mm) of lip/jaw movement associated with the opening for the [bVb] syllables in the words *baby* and *baboon*. Closed circles are used for syllables preceded by the phrase *Em's a* ____ and open triangles by the phrase *Emma's* _____. Error bars represent standard errors.

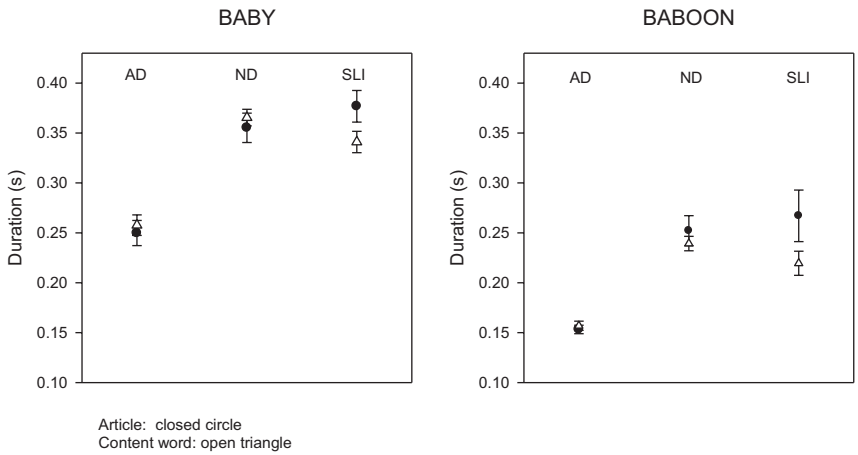


Fig. 5. Duration (in s) of lip/jaw movement associated with the open–close for the [bVb] syllables in the words *baby* and *baboon*. Closed circles are used for syllables preceded by the phrase *Em's a* ____ and open triangles by the phrase *Emma's* _____. Error bars represent standard errors.

produced larger amplitude movements in this syllable than their SLI peers or than adults. There was also an effect of linguistic context ($F(1, 30) = 9{\cdot}43$, $p = 0{\cdot}005$). Greater movement amplitudes for the syllable [bə] were observed in *Emma's baboon* than the *Em's a baboon* context. This was true

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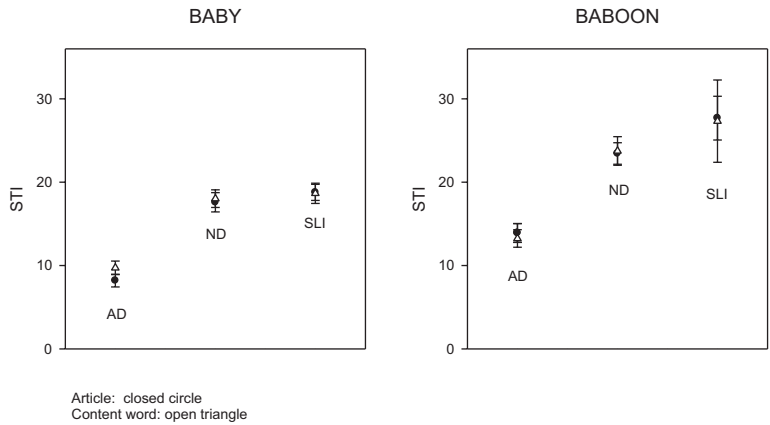


Fig. 6. STI values for SWSW and SWWS sequences. Closed circles are used for syllables preceded by a function word (e.g. *Em's a baby*) and open triangles by a weak syllable of a content word (e.g. *Emma's baby*). Error bars represent standard errors.

for all three groups, as indicated by no group*linguistic context interaction ($F(2, 30) = 0{\cdot}88$, $p = 0{\cdot}42$).

As shown in Figure 5, durations of the initial weak syllable in *baboon* showed a group effect ($F(2, 30) = 30{\cdot}34$, $p < 0{\cdot}0001$). Adults produced shorter-duration movements compared with both groups of children. There was an effect of linguistic context ($F(1, 30) = 4{\cdot}97$, $p = 0{\cdot}03$) with the weak syllable [bə] in the phrase *Emma's baboon* produced with shorter duration movements than in *Em's a baboon*. There also was a group*linguistic context interaction ($F(2, 30) = 3{\cdot}37$, $p = 0{\cdot}05$).

Kinematic analysis of variability. This analysis was extended beyond the word level, asking whether children (ND or SLI) or adults produce more variable movement sequences in alternating (SWSW) or non-alternating (SWWS) contexts. The focus of this analysis was the medial WS and WW components, all of which crossed word boundaries. As shown in Figure 6, there was a group effect for the STI ($F(2, 30) = 37{\cdot}77$, $p < 0{\cdot}001$). Post-hoc testing showed that adults differed from both groups of children, but children with SLI and ND were similar in their movement patterning variability. There also was an effect of prosodic context, with the SWSW sequence produced less variably than the SWWS sequence ($F(1, 30) = 52{\cdot}28$, $p < 0{\cdot}001$), with a trend toward a group*prosodic context interaction ($F(2, 93) = 2{\cdot}93$, $p = 0{\cdot}07$). There were no effects of context ($F(1, 30) = 0{\cdot}14$, $p = 0{\cdot}71$), and no group*context interactions ($F(2, 30) = 0{\cdot}04$, $p = 0{\cdot}96$). Both sentence frames (*Em's a* ____ and *Emma's* _____) were produced with similar degrees of movement patterning variability for all three groups of speakers.

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SUMMARY OF KINEMATIC RESULTS: Lexical items systematically varied in the amplitude of articulatory movements as a function of the sentence frame in which they were embedded. Duration measures showed the expected developmental effect, with adults producing shorter movements than children. Somewhat surprisingly, these slightly older children with SLI were similar to their younger ND peers in their organization of prosodic templates. For all three groups of speakers, the more problematic WW sequence was produced with more variable movement patterning than the alternating SW sequence.

DISCUSSION

In this study, we addressed three issues about the production of stress. First, we replicate prior findings based on children's overt error patterns, now including older children who are ND as well as those with SLI. We then turn to the central theme of this study, in which we use kinematic evidence to assess whether, at the word level, additional prosodic templates can be identified beyond the binary categories of iamb and trochee. Finally, we extend beyond the word, asking if well-formed rhythmic alternations (i.e. SW sequences) that cross word boundaries are produced with less variability than alternations that are poorly formed (i.e. WW sequences).

Children, especially those with language disorders, show difficulties with the production of unfooted weak syllables. It has been challenging to account for the variability in children's errors in these iambic structures. Transcription analysis, while essential, casts rather a wide net; sound and syllable omissions and substitutions may occur for a variety of reasons. Kinematic analysis allows a more fine-grained approach, providing insights into underlying factors that may influence production processes in young children. Many studies of children's stress production have relied on the productions of novel words (e.g. Gerken, 1996; Goffman, 1999; Schwartz & Goffman, 1995). While allowing for exquisite control of the stimuli, novel words are produced differently from familiar words (Heisler *et al.*, 2010; McMillan *et al.*, 2009). The use of natural as opposed to nonce stimuli on the one hand inherently includes confounds across prosodic, syntactic, lexical, and phonetic levels. On the other hand, more natural and systematic distinctions across prosodic categories can be identified. Because of the inherent infrequency of iambic nouns (Cutler & Carter, 1987) and the need to be restricted to labial consonants for the kinematic analysis, the words and phrases selected for this study (e.g. *Emma's baboon*) are probably unfamiliar to children. Thus, they contain the phonotactic characteristics of real words and phrases, but are likely similar to novel words in terms of children's lack of knowledge of them.

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Replication and extension of previous findings: preference for trochaic feet

Overall, the transcription results replicate earlier findings and support both adherence to a prosodic template and weakening of syllables that lack perceptual salience. Further, there is some suggestion that syntactic and other phonological factors may influence the accuracy of prosodically weak unfooted syllables. Four- to six-year-old children, especially those with SLI, omit weak syllables that are unfooted. Similar to ND two-year-olds, these older children showed sensitivity to the prosodic hierarchy (Demuth, 1996; 2001; Gerken, 1994; 1996), as demonstrated by the omission of syllables that do not fit a preferred SW prosodic structure. In this study, the weak syllable [bə] in the word *baboon* was omitted, while the [beI] in *baby* was not. An equally weak CV sequence containing a function word ([zə]) was almost never omitted, presumably because it could foot with the preceding strong syllable (i.e. *Em's a* ___).

One primary question was whether the same prosodic template applied in different language environments. As expected, increased omission errors occurred in unfooted weak syllables. Less predictably, these errors patterned differently across the two sentence frames, with more omissions occurring when the word *baboon* was preceded by *Em's a* than by *Emma's*. These two frames differed in several ways, most notably in morphosyntactic and phonetic structure.

Other types of error were also observed in this vulnerable prosodic environment. Children omitted the initial consonant in the word *baboon*, producing [əbun] instead. This error type occurred more frequently in children with SLI than in ND four-year-olds. As with the full-blown syllable omissions, these patterned differently across the two sentence frames. More segmental omissions occurred in the *Emma's* than the *Em's a* frame. Segmental substitution errors were also observed, but these did not pattern across the two sentence frames.

Because this study incorporated real rather than novel words, it is not possible to sort out the specific linguistic factors that led to these differences in omission errors as a function of the sentence frame in which the iambic word was embedded. Perhaps the most likely explanation can be found in the segmental make-up of the surrounding sentence. In the target [eməzbə bun] (i.e. *Emma's baboon*), the error is more likely to take the form [eməzə bun]. A full omission would result in [eməzbun], which includes a CC sequence rather than the preferred alternating CV structure. It has previously been suggested that phonological factors may influence the patterning of syllable and consonant omission errors (Gerken & Ohala, 2000). The grammatical inflection [z], rather than the [b], was maintained, suggesting sensitivity to inclusion of the more meaningful and grammatically salient element. The relative weighting of prosodic and morphosyntactic

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variables cannot be explicitly determined in the present experiment. However, it seems that a complex model that incorporates multiple levels of language processing is needed to explain children's errors.

In addition to omission errors, as predicted by a perceptually based account of children's difficulties with weak syllables (Echols, 1993; Snow, 1998), there was also an increase in segmental errors in the least prominent unfooted syllables. A higher proportion of segmental substitution errors occurred in the weak syllable [bə] (i.e. [bəbun]) compared with the strong syllable [beI] (i.e. [beIbi]). Examples of such errors were [kəbun] for *baboon* as produced by a child who was ND and [dəbum] for *baboon* by a child with SLI. Prior studies have relied on spontaneous data and thus not controlled the context of segmental errors (e.g. Echols, 1993; Snow, 1998), or have incorporated consonants that are variable in the speech of young children (Schwartz & Goffman, 1995). In these studies, multiple factors may have contributed to children's segmental variability. In the present case we were certain that the segments in the weak syllable could be easily produced by all of the children, since both the SW and the WS words used in this study included one of the earliest developing consonants, the bilabial [b]. Variable production of the segments in the syllable [bə] could only be attributed to their occurrence in prosodically weak environments.

Patterning of movement templates

Similar to previous work suggesting interactivity across levels of speech production (e.g. Baese-Berk & Goldrick, 2009; McMillan *et al*., 2009), prosodic structure is not tied to an individual lexical item. Thus, the present data are consistent with an emerging body of literature showing that domains of language processing interact in more complex ways than predicted by modular models of speech production (e.g. Cholin *et al*., 2004; Levelt *et al*., 1999). If there is indeed a catalog of highly frequent syllables available in a syllabary, these are not fixed entities, but are sensitive to other language demands and systematically vary based on these demands. The kinematic analyses of the patterning of rhythmic modulation revealed language effects. When the first syllable of an iamb (i.e. *baboon*) or a trochee (i.e. *baby*) was preceded by a content word (i.e. *Emma*) it was produced with larger amplitude movements than when it was preceded by an article (i.e. *a*). Thus, there were systematic differences in rhythmic structure that occurred as a function of language context. Because the present data were obtained from real rather than novel words embedded in a sentence frame (Goffman, 2004), it could not be ascertained whether morphosyntactic or phonological factors contributed to these systematic differences in the rhythmic template. All that is evident is that more reticulated distinctions occur than predicted by the binary iambic vs. trochaic categories.

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To fully understand this result, it would be necessary to include a range of different sentence frames that vary in lexical, syntactic, and segmental structure. As they stand, however, these results provide articulatory evidence that systematic reorganization of the prosodic template occurred for all groups of speakers, as a function of some aspect of language context. These data support that the standard two-category division of iambs and trochees is not sufficient to account for these type-differentiated errors. There are additional systematic prosodic templates within these categories that are produced by child and adult speakers. The same lexical item is produced with distinct prosodic templates in different sentence frames.

Variability of prosodic sequences across word boundaries

Articulatory findings demonstrated that syllables that contain non-canonical weak–weak sequences are produced more poorly than those with strong–weak alternations. This was even the case for adult speakers. When there were no overt errors, weak unfooted syllables were produced with increased movement variability. For all three groups (adults, ND, and SLI), increased kinematic variability was observed in the more problematic WW component of the [SW]W[S] sequence (e.g. [Emma's] [baboon]), compared with the WS component of the well formed [SW][SW] sequence (e.g. [Emma's][baby]). Even for adults, the string containing two contiguous weak syllables, one unfooted, was more variable. In this case, increased variability is indicative of a relatively poorly implemented motor pattern that varies on each rendition. Other studies have shown similar within-subject increases in articulatory variability as a function of complexity. For five-year-old children, phrases embedded in longer and more complex sentences are produced with increased articulatory movement variability compared to shorter and less complex phrases (Maner *et al.*, 2000). Similarly, in this study, the kinematic findings show that production variability is increased in unfooted syllables, even those that do not contain overt segmental errors.

Movement variability is complex. In prior studies about prosody we have found that early developing and frequently occurring trochaic nouns are actually produced with more variable movements than later developing and infrequently occurring iambic nouns (Goffman, 1999; Goffman & Malin, 1999). We argued that trochaic words may exploit an existing movement pattern and that speakers implicitly know that iambic words require increased precision. Such implicit knowledge is not relevant for difficult prosodic sequences that cross word boundaries. It is logical that the problematic sequence studied here actually showed an increase in variability.

The simplest view of variability is that it is an index of a less mature (Smith & Zelaznik, 2004) or an impaired (Huber, Stathopoulos,

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Ramig & Lancaster, 2003) system. Thelen and colleagues (e.g. Thelen & Smith, 1994) long ago suggested that variability should be viewed as a more complex construct and findings in the prosodic domain are consistent with this suggestion. In the present work, the more difficult weak–weak sequence was produced with more variability than a well-formed strong–weak alternation. In sum, within a lexical item, iambic forms are produced with increased precision (e.g. Goffman, 1999). Such precision is abandoned when more problematic prosodic sequences extend across word boundaries.

Differences across groups with implications for SLI

Children with SLI were included in this study because they have difficulties with many aspects of language production, including morphosyntactic, lexical, prosodic, and segmental domains (e.g. Leonard, 1998). In the present study, children with SLI differed from their ND peers primarily in the transcription analysis, producing an increased number of overt errors. While differences in movement duration, amplitude, and variability have been observed in other studies (e.g. Goffman, 1999; 2004), in the present findings the children with SLI were generally similar to their ND peers. Perhaps this was because, as a group, they were somewhat older. But, overall, these results suggest that, at the level of a single syllable or the organization of a two-syllable sequence that crosses word boundaries, children with SLI do not show particularly significant deficits. It may be that the production of novel words (i.e. new learning) or the organization of larger movement sequences reveals their deficit (Ullman & Pierpont, 2005).

What is especially striking in these findings is that adults and both groups of children represented identical prosodic categories. Even in the face of a less mature and more variable speech motor system, all three groups showed systematic differences in their organization of prosodic templates. All also showed reduced variability for well-formed compared with ill-formed cross-word rhythmic alternations. These findings together point to the idea that it is in the implementation not the representation that children differ from adults, at least in the production of these particular language structures.

CONCLUSIONS

The prosodic template account (e.g. Gerken, 1994; 1996) implies that there is a hierarchical structure in prosodic phonology, though the specific interactions of higher (e.g. morphological) and lower (e.g. segments, articulatory movement) levels of that hierarchy are not delineated. In the present case, we used speech motor and error analyses to assess components of this hierarchical structure. We found that two aspects of language

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influence rhythmic output in the speech motor domain. First, systematic subcategories of prosodic templates are observed that extend beyond the usually cited binary iambic and trochaic distinction. Second, unfooted syllables that occur across word boundaries are produced with relatively large movement variability, while those within words are produced with less variability.

The present results are consistent with an interactive view of language processing (Baese-Beck & Goldrick, 2009; Rapp & Goldrick, 2006). Rather than importing a syllabary of highly frequent forms, the phonetic details of production are influenced by shifts in morphological and segmental processes. These findings contribute to a growing body of evidence (e.g. Baese-Beck & Goldrick, 2009; Heisler *et al.*, 2010; McMillan *et al.*, 2009) demonstrating interactivity across phonetic and lexical, phonological, and morphological levels of language processing.

REFERENCES

Baese-Berk, M. & Goldrick, M. (2009). Mechanisms of interaction in speech production. *Language and Cognitive Processes* **24**, 527–54.

Boyle, M. K. & Gerken, L. (1997). The influence of lexical familiarity on children's function morpheme omissions: A nonmetrical effect? *Journal of Memory and Language* **36**, 117–28.

Burgemeister, B., Blum, L. & Lorge, I. (1972). *Columbia Mental Maturity Scale*, 3rd edn. New York: Harcourt Brace Jovanovich.

Cholin, J., Schiller, N. O. & Levelt, W. J. M. (2004). The preparation of syllables in speech production. *Journal of Memory and Language* **50**, 47–61.

Cutler, A. & Carter, D. M. (1987). The predominance of strong initial syllables in the English vocabulary. *Computer Speech and Language* **2**, 133–42.

Davis, B. L., MacNeilage, P. F., Matyear, C. L. & Powell, J. K. (2000). Prosodic correlates of stress in babbling: An acoustical study. *Child Development* **71**, 1258–70.

Dawson, J. & Stout, C. (2003). *The Structured Photographic Expressive Language Test-3*. San Antonio, TX: Harcourt Assessment.

Demuth, K. (1996). The prosodic structure of early words. In J. L. Morgan & K. Demuth (eds), *Signal to syntax: Bootstrapping from speech to grammar in early acquisition*, 171–84. Mahwah, NJ: Erlbaum.

Demuth, K. (2001). Prosodic constraints on morphological development. In J. Weissenborn and B. Hohle (eds), *Approaches to bootstrapping: Phonological, syntactic, and neurophysiological aspects of early language acquisition*, 3–21. Amsterdam: John Benjamins.

Demuth, K. (2003). The status of feet in early acquisition. *15th International Congress of Phonetic Sciences* (*ICPhS*), Universidad Antonima de Barcelona, 151–54.

Echols, C. H. (1993). A perceptually-based model of children's earliest productions. *Cognition* **46**, 245–96.

Gerken, L. A. (1994). Young children's representation of prosodic structure: Evidence from English-speakers' weak syllable omissions. *Journal of Memory and Language* **33**, 19–38.

Gerken, L. A. (1996). Prosodic structure in young children's language production. *Language* **72**, 683–712.

Gerken, L. A. & McGregor, K. K. (1998). An overview of prosody and its role in normal and disordered child language. *American Journal of Speech-Language Pathology* **7**, 38–48.

Gerken, L. A. & Ohala, D. (2000). Language production in children, In L. Wheeldon (ed.), *Aspects of language production*, 275–90. London: Psychology Press.

https://doi.org/10.1017/S0305000912000505 Published online by Cambridge University Press

Goffman, L. (1999). Prosodic influences on speech production in children with specific language impairment and speech deficits. *Journal of Speech, Language, and Hearing Research* **42**, 1499–517.
Goffman, L. (2004). Kinematic differentiation of prosodic categories in normal and disordered language development. *Journal of Speech, Language, and Hearing Research* **47**, 1088–1102.
Goffman, L., Heisler, L. & Chakraborty, R. (2006). Mapping of prosodic structure onto words and phrases in children's and adults' speech production. *Language and Cognitive Processes* **21**, 25–47.
Goffman, L. & Malin, C. (1999). Metrical effects on speech movements in children and adults. *Journal of Speech, Language, and Hearing Research* **42**, 1003–1015.
Goffman, L. & Smith, A. (1999). Development and phonetic differentiation of speech movement patterns. *Journal of Experimental Psychology: Human Perception and Performance* **25**, 649–60.
Grigos, M. & Patel, R. (2007). Articulator movement associated with the development of prosodic control in children. *Journal of Speech, Language, and Hearing Research* **50**, 119–30.
Hayes, B. (1995). *Metrical stress theory*. Chicago: University of Chicago Press.
Heisler, L., Goffman, L. & Younger, B. (2010). Lexical and articulatory interactions in children's language production. *Developmental Science* **13**, 722–30.
Huber, J. E., Stathopoulos, E. T., Ramig, L. O. & Lancaster, S. L. (2003). Respiratory function and variability in individuals with Parkinson Disease: Pre- and post-Lee Silverman Voice Treatment. *Journal of Medical Speech-Language Pathology* **11**, 185–201.
Leonard, L. B. (1998). *Children with specific language impairment*. Cambridge, MA: MIT Press.
Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: MIT Press.
Levelt, W. J. M., Roelofs, A. & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences* **22**, 1–75.
MacNeilage, P. F. & Davis, B. L. (2000). On the origin of internal structure of word forms. *Science* **288**, 527–31.
Maner, K., Smith, A. & Grayson, L. (2000). Influences of utterance length and complexity on speech motor performance in children and adults. *Journal of Speech, Language, & Hearing Research* **43**, 560–73.
MathWorks (1993). *Matlab: Higher performance numeric computation and visualization software* [computer program]. Natick, MA: Author.
McMillan, C. T., Corley, M. & Lickley, R. (2009). Articulatory evidence for feedback and competition in speech production. *Language and Cognitive Processes* **24**, 44–66.
Prince, A. (1990). Quantitative consequences of rhythmic organization. In M. Ziolkowski, M. Noske & K. Denton (eds), *Papers from the 26th regional meeting of the Chicago Linguistic Society*: The parasession on the syllable in phonetics and phonology, 355–98. Chicago, IL: Chicago Linguistic Society.
Rapp, B. & Goldrick, M. (2006). Speaking words: Contributions of neuropsychological research. *Cognitive Neuropsychology* **23**, 39–73.
Reynell, J. & Gruber, C. (1990). *Reynell Developmental Language Scales-US Edition*. Los Angeles: Western Psychological Services.
Robbins, J. & Klee, T. (1987). Clinical assessment of oropharyngeal motor development in young children. *Journal of Speech and Hearing Disorders* **52**, 271–77.
Schwartz, R. G. & Goffman, L. (1995). Metrical patterns of words and production accuracy. *Journal of Speech and Hearing Research* **38**, 876–88.
Smith, A. & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research* **41**, 18–30.
Smith, A., Goffman, L., Zelaznik, H., Ying, S. & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. *Experimental Brain Research* **104**, 493–501.

https://doi.org/10.1017/S0305000912000505 Published online by Cambridge University Press

Smith, A., Johnson, M., McGillem, C. & Goffman, L. (2000). On the assessment of stability and patterning of speech movements. *Journal of Speech, Language, and Hearing Research* **43**, 277–86.

Smith, A. & Zelaznik, H. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology* **45**, 22–33.

Snow, D. (1998). A prominence account of syllable reduction in early speech development: The child's prosodic phonology of tiger and giraffe. *Journal of Speech, Language, and Hearing Research* **41**, 1158–70.

Thelen, E. & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Ullman, M. T. & Pierpont, E. I. (2005). Specific language impairment is not specific to language: The procedural deficit hypothesis. *Cortex* **41**, 399–433.

Vihman, M. M., DePaolis, R. A. & Davis, B. L. (1998). Is there a 'trochaic bias' in early word learning? Evidence from infant production in English and French. *Child Development* **69**, 935–49.

Zamuner, T. & Gerken, L. A. (1998). Young children's production of coda consonants in different prosodic environments. In E. Clark (ed.), *Proceedings of the Annual Child Language Research Forum 29*, 121–28. Stanford, CA: Center for the Study of Language and Information.

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