Learning to assign lexical stress during reading aloud:

Corpus, behavioural, and computational investigations

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Abstract

Models of reading aloud have tended to focus on the mapping between graphemes and phonemes in monosyllables. Critical adaptations of these models are required when considering the reading of polsyllables, which constitute over 90% of word types in English. In this paper, we examined one such adaptation – the process of stress assignment in learning to read. We used a triangulation of corpus, behavioural, and computational modeling techniques. A corpus analysis of age-appropriate reading materials for children aged 5 to 12 years revealed that the beginnings and endings of English bisyllabic words are highly predictive of stress position, but that endings are more reliable cues in texts for older children. Children aged 5-12 years revealed sensitivity to both the beginnings and endings when reading nonwords, but older children relied more on endings for determining stress assignment. A computational model that learned to map orthography onto stress showed the same age-related trajectory as the children when assigning stress to nonwords. These results reflect the gradual process of learning the statistical properties of written input and provide key constraints for adequate models of reading aloud.

Key Words: lexical stress; stress assignment; probabilistic cues; statistical learning; orthography; reading; reading aloud; reading acquisition; reading development; visual word recognition

Most studies of learning to read aloud have focused on how children acquire knowledge of the correspondences that exist between orthography and segmental phonology, when reading monosyllabic words and nonwords. It has been demonstrated that this is an enormously complex process and that there are multiple ways in which it can be disordered (see Bishop & Snowling, 2004, for a review). There is growing interest in how orthography maps onto suprasegmental phonology, in particular, how lexical stress is assigned during the reading aloud of polysyllables in languages such as English, which do not have fixed patterns of stress and do not employ diacritics to mark stress. There is interest in stress assignment in terms of its relationship to other aspects of reading acquisition (Whalley & Hansen, 2006; Wood, 2006) and in terms of what it can reveal about disorders in the reading system (Burani & Arduino, 2004; Richardson, Thomson, Scott, & Goswami, 2004). Yet, the link between orthography and patterns of lexical stress in children's reading materials, and the trajectory of stress assignment during children's reading development, are poorly understood.

In this paper, we contribute towards providing an integrative account of stress assignment during children's reading aloud in English through a combination of three methods: corpus analyses of children's age-appropriate reading materials, behavioural investigation of stress assignment by children at different stages of reading development, and computational modeling. We begin by discussing current models of reading aloud and the challenge posed by stress assignment during the reading of polysyllables. We then review data on the link between orthography and patterns of lexical stress in adult reading materials, and review the limited number of previous behavioural studies that have directly assessed stress assignment during reading development.

Current models of reading aloud and the challenge of stress assignment

During reading aloud in English, lexical stress must be assigned in order for polysyllables, over 90% of word types in English (CELEX database: Baayen, Pipenbrock, & Gulikers, 1993), to be pronounced. While some languages exhibit fixed patterns of lexical stress where placement of stress is highly predictable (e.g., French), other languages such as Italian, Dutch and English exhibit variable patterns of lexical stress. For example, in English, while the majority of polysyllabic words have first syllable stress, a large proportion of words – over 20% – do not (CELEX database: Baayen, Piepenbrock & van Rijn, 1993). So how does the reading system learn to apply first-syllable stress for 'zebra' but second-syllable stress for 'giraffe' and first-syllable stress for 'listen' but second-syllable stress for 'explain'? Moreover, how is it that a nonword like 'gefoon' elicits second-syllable stress in the majority of readers? Current models of reading aloud have very little to say about stress assignment because such models have generally focused on the reading of monosyllables where stress assignment is not an issue.

Contemporary computational models of reading aloud provide insight regarding the mapping of orthographic information onto phonemes (Coltheart et al., 2001; Harm & Seidenberg, 2004; Perry, Ziegler, & Zorzi, 2007; Seidenberg & McClelland, 1989). They have been at the centre of debate over the representational units required for forming these mappings (Ziegler & Goswami, 2005) and at the centre of discoveries concerning the nuanced effects of the consistency and the regularity of these mappings as constraints on the computational reading process (Jared, 2002; Zevin & Seidenberg, 2006).

With this focus on grapheme-to-phoneme mappings, the debate regarding competing models has converged to the question of whether the mapping between written and spoken forms of words is mediated by a single-route or a dual-route. The single-route perspective assumes that the statistical consistencies between graphemes and phonemes are learned by a mechanism where all sources of information are available in parallel and that this mechanism operates on both words and nonwords (Seidenberg & McClelland, 1989). The alternative dual-route view is that the mapping is served by a system that processes the regularities between graphemes and phonemes serially, via a set of rules, and additionally by a separate system that consults a lexicon for the pronunciation of the whole word (Coltheart et al., 2001). Note that in Perry, Ziegler and Zorzi's (2007) dual route model implementation, graphemes are converted to phonemes via an associative network that learns the mappings. Words, then, are read by a combination of the grapheme-phoneme route and the lexical route. While both routes will attempt to process nonwords, as there will be no corresponding lexical entries for nonwords these can only be read via the grapheme-phoneme route.

How can these general views of the reading system be extended to include stress assignment? For the dual-route model, stress assignment could be either a property of lexical representations or of the grapheme-phoneme correspondence system. However, storing stress information only in the lexical route would be problematic because polysyllabic nonwords require stress assignment during reading aloud, and there is predictability in the different stress patterns assigned to particular nonwords (Arciuli & Cupples, 2007; 2006; Kelly, 2004). Default stress assignment cannot apply for all stimuli without a lexical representation. One solution, then, for this class of models is to propose that stress is assigned in a rule-based system analogous to the grapheme-to-phoneme nonlexical route. Rastle and Coltheart (2000) derived one such rule-based algorithm for stress assignment as an addendum to the dual-route cascaded model of reading, that was designed to simulate human performance for reading bisyllabic nonwords. The algorithm involved searching through the letter string for morphemes (to identify the presence of 54 prefixes and 101 suffixes, as in Fudge, 1984), and then consulted a database for information concerning whether each morpheme carried stress or not (e.g., the suffix '–ing' rarely carries stress in English). The algorithm resulted in correct assignment of stress for a large proportion of English words, and agreed with the majority of participants' decisions regarding stress placement in nonwords when they contained identifiable morphemes. Yet, the algorithm performed poorly when no pre-defined prefixes or suffixes were present in the nonwords (Kelly, 2004; Seva, Monaghan, & Arciuli, 2009).

In single-route models, stress assignment must operate using similar principles to those applied for learning the grapheme-phoneme mappings, regardless of whether the input is a real word or a nonword. We posit that certain orthographic patterns are probabilistically associated with stress position, which the model, after sufficient exposure to these statistics of the lexicon, can discover and apply to any input (including unfamiliar real words and nonwords). Zevin and Joanisse (2000) undertook pilot modeling that examined the consistencies potentially available in the orthography, morphology, and phonology of words for determining stress assignment, and found that such cues were highly predictive of stress position (see also Daelemans, Gillis, & Durieux, 1994, for a word-analogy approach to stress assignment in Dutch). Based on earlier corpus and behavioural work by Arciuli and colleagues, Seva et al. (2009) trained a connectionist model that learned to map written bisyllabic English words onto stress position with a high degree of accuracy, indicating that statistical generalities in the correspondence between letters and stress position are potentially available to the reading system.

The link between orthography and stress position

It has been known for some time that there are statistical regularities in orthography that reflect stress position, however, few studies have attempted to determine whether particular parts of the written word form are especially useful for stress assignment. The distributions of phonemes and letters at the very beginning and the very ending of words have been found to be particularly reliable indicators of other aspects of language processing including word boundaries (Hockema, 2006) and grammatical category (Arciuli & Monaghan, 2009). Similarly, cues to stress position appear to be present in the initial and final parts of words as manifested in stress-shifting derivational and inflectional morphemes (Fudge, 1984; Rastle & Coltheart, 2000); yet, the value of such cues has been shown to extend beyond morphology (e.g., Arciuli & Cupples, 2006; 2007; Kelly, 2004).

Arciuli and colleagues conducted large-scale analyses of adult corpora and revealed that there are extensive probabilistic cues to lexical stress in English orthography. For example, in bisyllabic words, ending sequences such as '-ip' and '-ock' are strongly associated with first syllable stress while different endings such as '-ibe' and '-oin', are associated with second syllable stress. Adult participants were shown to be sensitive to these probabilistic cues (Arciuli & Cupples, 2006, see also Kelly, Morris & Verrekia, 1998). In a related study, it was shown that word-beginnings, also, provide probabilistic cues to stress and that adult participants show sensitivity to these cues (Arciuli & Cupples, 2007). In both studies, these orthographic markers of stress were not derived from morphology. Indeed, only 14% of the 340 word endings analysed by Arciuli and Cupples (2006) appear in the comprehensive list of morphemes provided by Fudge (1984).

Interestingly, the findings from these studies point to endings as more reliable markers of lexical stress; however, the relative importance of beginnings versus endings in marking lexical stress has not been investigated in a single study, and the extent to which readers rely on each was an open empirical question – one which we sought to address in the present study. In addition, the role of beginnings and endings as cues to lexical stress, in children's age-appropriate reading materials, had not been examined. Children are exposed to an increasing number and variety of written words as they grow older. It is possible that that the relative importance of beginnings and endings, as cues to stress, differs according to the nature and size of the written lexicon to which children are exposed during their primary years (i.e., ages 5-12 where formal schooling emphasises literacy development). The relative role of beginnings and endings also has theoretical implications for an adequate computational model of reading. For example, one of the main principles of many dual-route models of reading is that the sublexical, rule-based route proceeds serially from left to right through the letter string, yet if it can be demonstrated that endings are more influential for stress assignment, then this questions the *seriality of the reading process* – the reader would have to get to the end of the word before stress can be assigned, and therefore before a full pronunciation can be generated. We return to this point in the General Discussion.

Learning to assign lexical stress during reading acquisition

While a critical aspect of the single-route, statistical consistency approach is that the mapping between written and spoken forms of words is *learned* there is very little empirical data concerning developmental constraints on the reading process.

Typically, previous studies that have examined the development of stress assignment have not been designed to elucidate highly specified reading processes. Several studies have shown that the frequency of morphologically derived stress-changing suffixes has an influence on children's stress assignment. For example, Jarmulowicz and colleagues have examined the relationship between particular suffixes (e.g., -tion, -ity, -ic) and stress assignment. Using polysyllabic words and nonwords containing these suffixes it was found that 9 year old children were better judges of where primary stress should fall when compared with 7 year olds. The age advantage increased for more frequent suffixes (Jarmulowicz, 2002; see also Jarmulowicz, Taran & Hay, 2008). However, whereas written materials were analysed to determine suffix frequency, the study was not concerned with reading processes and did not examine children's productions during reading aloud (rather, the children made auditory judgements about which stress patterns 'sounded better').

In a related study, Jarmulowicz, Hay, Taran, and Ethington (2008) examined the relationship between oral language and reading ability. Specifically, they investigated the relationship between metalinguistic phonological and morphological skills – including those relating to the production of stress changing suffixes – and reading ability in third grade children. Findings showed that morpho-phonological awareness was related to decoding ability. This study contributes to a growing body of research indicating the importance of lexical stress in both typical and disordered spoken language acquisition (e.g., Arciuli & McLeod, 2008; Paul et al., 2005; Weber, Hahne, Friedrich & Friederici, 2005; Whalley & Hansen, 2006; Wood, 2005).

Some studies have focused on languages other than English. Studies of Greek have investigated stress assignment during reading aloud in secondary school children in Grade 7 and above (Protopapas, 2006; Protopapas, Gerakaki & Alexandri, 2006). These studies have investigated the possible sources of information concerning stress assignment in Greek, including orthographic cues, diacritics that mark stress, and a default metrical pattern, and have argued that the relative usefulness of each of these cues may vary developmentally. Protopapas and Gerakaki (2009) tested these sources of information in younger children's reading of words and nonwords (children in Grades 2, 3, and 4). They suggested that orthographic cues derived from the written lexicon may be the primary source of information about patterns of lexical stress in Greek. It is not yet known which parts of the written word (e.g., beginnings or endings) children are attending to when assigning stress during reading aloud in Greek.

Gutierrez-Palma and Reyes (2007) examined stress assignment in Spanish. Like Greek, Spanish employs diacritics, exhibits some orthographic markers of stress and appears to have a default stress pattern. Similarly to Jarmulowicz et al. (2008), Gutierrez-Palma and Reyes (2007) explored the notion that lexical stress is associated with salient speech units which are relevant for reading ability. They demonstrated that children aged

7 to 8 years show awareness of how stress is assigned when reading aloud in Spanish and that increased sensitivity to stress assignment (particularly when reading nonwords) is related to higher reading ability.

Aims of the current study

Assignment of lexical stress – a key process in polysyllabic reading – is both of practical import in developmental/educational research as well as providing valuable constraints for computational models of reading aloud. Here we combined corpus analyses, behavioural testing, and computational modeling, to comprehensively investigate how children learn to assign stress during reading aloud in English. We aimed to:

1. Investigate through corpus analyses the extent to which the beginnings and/or endings of words (in terms of orthography) serve to predict patterns of lexical stress in the age-appropriate reading materials to which children are exposed;
2. Determine through behavioural testing the extent to which children at different stages of reading development are sensitive to beginnings and endings as cues to lexical stress when reading aloud;
3. Examine the developmental trajectory of a connectionist computational model in relation to the developmental data on stress assignment.

Study 1: Corpus Analyses

Previous corpus analyses of the adult English lexicon have indicated that beginnings and endings are valuable contributors to predicting stress position in polysyllabic words (Arciuli & Cupples, 2007; 2006). Here, we investigated whether these statistical cues to stress are available in the age-appropriate reading materials to which children are exposed when learning to read.

Method

The corpus was derived from Section I of the Educator's Word Frequency Guide (WFG, Zeno, Ivens, Hillard, & Duvvuri, 1995). The WFG is constructed from 60,527 paragraph samples taken from 16,333 written texts. In the corpus, there are approximately 155,000 different words, and the total corpus size is over 17 million words. Each text was graded using readability measures and its age-appropriate level was determined for readers at 13 different grades, covering the age range 5 to 18 in the American and British schooling systems. The 19,468 words with frequency at least 1 per million were included in Section I of the WFG.

The pronunciation of each word was determined by comparing the WFG wordlist with the CELEX database (Baayen et al., 1993). When the pronunciation was ambiguous with respect to the orthography from WFG, then the most frequent pronunciation cited in CELEX was used. The analyses were applied to all the bisyllabic words extracted from the WFG. There were 6,531 such words altogether, 5,393 with first- and 1,138 with second-syllable stress. In our analyses, we focused on the corpora for children between the ages of 5 and 12, because, in most countries, this is the age range of children undertaking primary school education where there is an emphasis on basic literacy. After this point, it is expected that most typically developing children that have had uninterrupted formal schooling are generally able to read accurately and fluently (Wolf, 2008).

Similar to the analyses of Arciuli and Cupples (2007), for each word, we took the letters that corresponded to the pronunciation up to and including the first vowel and vowel cluster as a beginning cue (i.e., “ze” in “zebra” or “gi” in “giraffe”). As in Arciuli and Cupples (2006) the ending cue was taken to be the letters that corresponded to the rime of the second syllable (i.e., “a” in “zebra”, “affe” in “giraffe”). Each word, then, had just one beginning and one ending cue encoded as a binary variable. For each of our age groups we conducted a stepwise discriminant analysis with either the word beginnings or endings as independent variables, and whether the word had first- or second syllable stress as the dependent variable. We selected all the words with a frequency greater than 2 per million. We conducted both type and token analyses. In the former, each word was equally weighted in the analysis, and in the latter each word was weighted according to its frequency in contributing to the analyses. For each discriminant analysis, the two groups (first- or second-syllable stress) were equally weighted, so the model attempted to maximize the discrimination for both groups, and not just the group with the highest token frequency. We repeated these analyses using only the monomorphemic words contained within the WFG, as classified by the CELEX database (Baayen et al., 1993), in order to determine whether the role of beginnings and endings provide cues to stress in all words and not just those that contain morphologically derived affixes. In terms of number of letters the length of beginnings and of endings ranged from 1-6 letters. Beginnings tended to be shorter than endings. Table 1 shows the number of distinct beginnings and distinct endings for all words and for monomorphemic words – in the reading materials for each age.

INSERT TABLE 1 HERE

Results and Discussion

For ease of interpretation, we focused on four age groupings: 5/6 years, 7/8 years, 9/10 years and 11/12 years. The number of bisyllabic words with stress on each position for these four age groups is shown in Table 2. The overlap between the sets of words at different ages was substantial, thus the later age word sets tended to contain most of the words at an earlier stage, plus additional words. Of the words in the 5/6 age sets, 93.8% were in the 7/8 age sets. Of the 7/8 age sets, 92.8% were in the 9/10 set, and of this set, 96.1% were also in the 11/12 word set.

INSERT TABLE 2 HERE

At each age, both beginnings and endings in both type and token analyses were highly significantly effective in determining stress position, all Wilk's lambda $<=$ .53, all $p <$ .001. Figure 1 shows the results for beginnings and endings for each age group for the token and the type analyses.

INSERT FIGURE 1 HERE

Over all age-appropriate corpora of written words, word endings were more accurate at predicting stress position than were word beginnings for the type analysis, $F(1, 7) = 41.16$, $p < .001$, $\eta^2 = .86$ and for the token analysis, $F(1, 7) = 445.71$, $p < .001$,

$\eta^2 = .99$. For the token analysis, the difference between beginnings and endings in terms of how accurately they classified words increased with each age-level, with endings remaining as strong predictors, and beginnings reducing in predictive value with age. A correlational analysis of the difference between beginnings and endings classifications and age was highly significant, Spearman's *rho* = .96, $p < .001$. But for the type analysis, the correlation was not significant, Spearman's *rho* = -.60, p = .12.

When we conducted the same analyses on only monomorphemic words we found an almost identical pattern of results. Both beginnings and endings were highly significant in classifying words by stress position, all Wilk's lambda <= .59, all $p < .001$, as shown in Figure 2. ANOVAs indicated that endings were more effective at classifying words according to stress position than endings for both the type analysis, $F(1, 7) = 216.63$, $p < .001$, $\eta^2 = .97$, and for the token analysis, $F(1, 7) = 732.58$, $p < .001$, $\eta^2 = .99$. There was again a significant relationship between age and differences in the accuracy of classifications based on beginnings and endings for the token analysis, Spearman's *rho* = .96, $p < .001$. This indicates that, with age, the lexicon is more effectively classified by endings than beginnings, even for words with no explicit morphology. However, this was once again not significant for the type analysis, *rho* = .17, $p = .66$.

INSERT FIGURE 2 HERE

The corpus analyses confirmed previous studies of adult lexica that indicated that both the beginnings and endings of words are extremely useful in categorizing words according to their stress position. The beginning "ze", from zebra, provides information that the word carries first-syllable syllable stress, however, of increasing importance, the word's ending, "a", also indicates that stress is carried on the first syllable. Arciuli and Cupples (2006; 2007) found similar results for adult corpora, and the current study demonstrates that this asymmetry of information within the lexicon was apparent for all age-appropriate groups of words in children's reading materials. Consequently, the information about the status of endings as particularly strong cues to stress appears to be available to young children. Even as early as age 5/6, the words that children are exposed to during their reading reflect the greater reliability of endings in indicating stress position. These patterns were almost identical in our two separate analyses of both all words and just the monomorphemic words. This indicates that the notion of stress-influencing affixes (e.g., Fudge, 1984) can be extended as a more general property throughout the lexicon. Word endings, not only morphologically derived suffixes, provide accurate information about stress position.

Furthermore, the accuracy of the discriminant analyses was greatest for the earliest age-appropriate grouping of words. These words carried more orthographic information about stress position than the words that children were exposed to at later stages of reading development. However, the greater overall accuracy of the early ages was due in part to the smaller set of age-appropriate words for these groups, though the improvement over chance was still highly significant for these earlier age-appropriate sets of words.

Though we have established that there is substantial orthographic information to indicate stress position, and that this can be found in the very beginning and end of words at various ages, the corpus analyses cannot show whether such information is actually utilised by children when they are learning to read. In the Study 2 we constructed a set of nonwords based on cues that were found to be reliable indicators for stress assignment in the corpus analyses, and tested children's sensitivity to these cues at different ages, from very early stages of learning to read until later levels of reading development. We tested children on nonwords so we could be certain that the children had not seen the items before and so would not respond according to a stored lexical representations of polysyllabic words, thus revealing the child's sensitivity to the orthographic form of the letter string. Testing nonwords also provides critical data for comparing computational models of reading aloud which differ with respect to their predictions of how regularities in mapping beginnings and endings onto stress position would influence naming performance. In particular, dual-route, serial models of reading may struggle to accommodate the special status of word endings in children's growing written lexicons, whereas single-route models that respond to the available statistical information would predict that endings become more influential in guiding stress position with increasing age, as revealed in the corpus analyses.

Study 2: Behavioural Investigation of Stress Assignment

In Study 2, we tested children aged between 5 and 12 years on their reading of bisyllabic nonwords. Our aim was to focus on how children assigned stress when reading aloud. We also wanted to test the extent to which word beginnings and endings would both combine and conflict in determining responses to stress position. So, half of the nonwords had consistent cues to stress position from the nonwords' beginnings and endings, and half had conflicting cues – where the beginning of the nonword was typically associated with first syllable stress and the ending with second syllable stress, or vice versa. The results enable us to test whether children are sensitive to and influenced by both beginnings and endings, or whether beginnings or endings are dominant in determining stress assignation.

Method

Participants. The participants were 186 primary aged children from 6 schools in New South Wales, Australia. There were 7 children of 5 years, 31 of 6 years, 29 of 7 years, 25 of 8 years, 27 of 9 years, 28 of 10 years, 25 of 11 years, and 14 of 12 years of age. As in Study 1, we grouped these children into four age groups: 5/6 (n = 38), 7/8 (n = 54), 9/10 (n = 55), 11/12 (n = 39). Parents of the participants confirmed that their children were native speakers of English without hearing or learning problems. Classroom teachers confirmed that each child in the study was reading at an age-appropriate level. In Australia, children begin formal reading instruction in their first year of primary school, in Kindergarten, and this was certainly the case for the participants in our study.

Materials. Using the results of the corpus analyses we identified beginnings that were strongly associated with first-syllable stress and endings that were strongly associated with second-syllable stress in the reading materials for all age groups. Moreover we ensured that these beginnings and endings were strong predictors in both the full analyses and in the analyses of only the monomorphemic words. So, for instance, the beginnings ‘ma-’ and ‘co-’ and the endings ‘-ol’ and ‘-et’ were highly associated with first-syllable stress in both morphologically complex and monomorphemic words. In contrast, the beginnings 'be-' and 'a-' and the endings '-oon' and '-ade' were associated with second-syllable stress. We constructed four types of nonword, varying whether the beginning and ending cue indicated first- or second-syllable stress. There were 6 nonwords with beginnings and endings both indicating first-syllable stress (first-first), 6 with beginnings and endings both indicating second-syllable stress (second-second), 6 with beginnings indicating first-syllable stress and endings indicating second-syllable stress (first-second), and 6 with beginnings indicating second syllable stress and endings indicating first syllable stress (second-first).[1] The youngest age group (5/6 years) were only tested on 4 of each type of nonword, due to testing fatigue. The nonwords are shown in Table 3.

INSERT TABLE 3 HERE

Procedure. Children were tested individually in a quiet room. Nonwords were presented on individual cards, and children were told they were to try and read these nonsense words and that there was no right or wrong answer. As we were interested in stress assignment (rather than the realisation of particular phonemes), and we were using nonsense words that can be pronounced in a number of different ways, we employed a liberal coding criteria (as used in Rastle & Coltheart, 2000). Responses were coded in

[1] A reviewer pointed out that some of our nonwords contain embedded words. Any such embedded items are monosyllabic, thus, it seems unlikely that they contributed prior lexical knowledge of stress assignment. Some of our stimuli contained medial consonant clusters, however, we believe that these medial consonant clusters did not affect the behavioural results. For words with medial consonant clusters around the syllabic boundary (as in the nonwords 'mandol' or 'ambey') 81.3% of bisyllabic words in CELEX have first syllable stress. For words without a medial consonant cluster around the syllabic boundary, 87.5% of bisyllabic words in CELEX have first syllable stress. If a medial consonant cluster affects stress position for the nonwords we would expect a slight bias against word endings influencing stress position as the child learns more about the language, rather than the observed growing influence of endings. Furthermore, recent data from Australian children has indicated that clusters are produced at mastery level by 5-6 years of age (McLeod & Arciuli, 2009).

terms of whether the child's production was bisyllabic or not. Then, for bisyllabic responses we coded for first-syllable stress, second-syllable stress, or even stress. The coding was conducted by investigators without knowledge of the experimental conditions. A random sample of 10% of the participant data was coded for stress assignment by an independent rater and agreement was found to be just over 80%.

In the analyses, the dependent variable was the proportion of responses with first syllable stress. These were computed in two ways: first, as a proportion of all bisyllabic responses with either first- or second-syllable stress to directly compare the bias towards stress position; and second, as a proportion of all the nonwords presented to the child, regardless of whether the child's response was bisyllabic.

Results and Discussion

Proportion of all bisyllabic responses. Figure 3 shows the percentage of each response type for each age group reading each of the four types of nonwords. In order to ascertain whether responses varied according to age and whether beginnings or endings exerted an influence on children's decisions about stress position, we performed a 4 x 2 x 2 ANOVA on the proportion of bisyllabic responses that had first syllable stress, with age as between subjects variable (age groups 5/6, 7/8, 9/10, and 11/12), and as within subjects variables whether beginnings indicated first or second-syllable stress and whether endings indicated first- or second-syllable stress. There was a significant main effect of age, $F(3, 182) = 5.10$, $p < .005$, $\eta^2 = .08$, with age group 11/12 making significantly fewer first-syllable stress responses than the other age groups over all nonword types, all $p < .05$. There was a significant main effect of beginnings, $F(1, 182) = 67.85$, $p < .001$, $\eta^2 =$

.27, with first-syllable stress beginnings resulting in more first syllable responses than beginnings indicating second syllable stress. There was also a significant main effect of ending cues, $F(1, 182) = 244.36$, $p < .001$, $\eta^2 = .57$, with ending cues indicating first-syllable stress resulting in more first syllable stress responses than endings indicating second-syllable stress. These main effects indicate that, overall, children were sensitive to both the beginning and the ending cues as indicators stress position.

INSERT FIGURE 3 HERE

There was a marginally significant interaction between age group and beginning cues, $F(3, 182) = 2.40$, $p = .07$, $\eta^2 = .04$. There was a significant interaction between age group and ending cues, $F(3, 182) = 14.36$, $p < .001$, $\eta^2 = .19$. This was due to an enhanced sensitivity to endings as markers of stress with increasing age. Age groups 5/6 and 7/8 showed a smaller difference in first syllable stress responses to nonwords with first syllable stress cues compared to second syllable stress cues (12.2% and 19.9% for ages 5/6 and 7/8, respectively) than did age groups 9/10 and 11/12 (35.6% and 42.1%, respectively), all $p < .001$, but age groups 5/6 and 7/8 did not differ, and nor did age groups 9/10 and 11/12, both $p > .15$.

There was a significant interaction between beginning cues and ending cues, $F(1, 182) = 22.14$, $p < .001$, $\eta^2 = .11$, with ending cues having a larger effect when the beginnings cue indicated second syllable stress than when beginning cues indicated first syllable stress. The three-way interaction was not significant, $F < 1$.

Proportion of all nonwords presented to the child. We repeated the ANOVA with proportion of responses with first syllable stress position as the dependent variable, without restricting the responses only to the bisyllabic response set as in the first analysis. The results were very similar. There was a significant main effect of age, $F(3, 182) = 10.35$, $p < .001$, $\eta^2 = .15$, a significant main effect of beginnings, $F(1, 182) = 71.06$, $p < .001$, $\eta^2 = .28$, and a significant main effect of ending cues, $F(1, 182) = 324.66$, $p < .001$, $\eta^2 = .64$. The two-way interactions were all significant, for age and beginning cues, $F(3, 182) = 3.06$, $p < .05$, $\eta^2 = .05$, for age and ending cues, $F(3, 182) = 14.68$, $p < .001$, $\eta^2 = .20$, and for beginning cues and ending cues, $F(1, 182) = 25.35$, $p < .001$, $\eta^2 = .12$. The three-way interaction was again not significant, $F < 1$.

The results demonstrate two principal effects of learning stress assignment in reading in English. First, young children indicate a greater tendency than older children to pronounce nonwords with first syllable stress. This suggests an over-generalisation, consistent with the distribution of first- and second-syllable stressed words in the language, evident from the corpus analyses – 85% of the bisyllabic words in the WFG database have first syllable stress. However, children aged 5/6 matched their responses closely to the actual distributions in the lexicon based on age-appropriate reading materials: 80% of 5/6 year olds' responses were pronounced with first syllable stress. Yet it would appear that as the child has more practice with reading, and more exposure to the written lexicon, this bias reduces with age: 7/8 year olds pronounced 73%, 9/10 year olds pronounced 71%, and 11/12 year olds pronounced 58% with first syllable stress.

The second principal property is the change in the prominence of the cues as age increases. At age 5/6, stress was generally placed on the first syllable, and beginning and ending orthographic cues had a small influence on stress assignment. As age increased, however, both word beginnings and endings had more of an effect on readers' responses, as reflected in the interactions between age group and each type of cue. Children, as they extend their lexicon for reading, learn to rely more heavily on the regions of the word that are most predictive of stress position.

The design of the nonwords enables us to test the relative dominance of beginnings versus endings in determining children's responses to the nonwords. The proportion of nonwords with inconsistent beginning and ending cues to stress position that are pronounced according to the stress pattern of the beginning or the ending indicates which is most relied upon for stress pronunciation. We counted the proportion of stressed responses that were consistent with the beginning cues for these nonwords, and the results are shown in Figure 4. Values greater than .5 indicate that responses were more often in accordance with the statistical distributions of the beginning cues, whereas values lower than .5 indicate greater reliance on the ending cues. A value of .5 would indicate that 50% of the time participants responded to the beginning cue and 50% of the time they responded to the ending cue. An ANOVA with age group as factor indicated a significant main effect, $F(3, 182) = 10.82$, $p < .001$, $\eta^2 = .15$. Tukey's post hoc tests indicated that age group 5/6 relied less on endings than the other age groups, all $p < .05$, and age group 7/8 relied less on endings than the oldest age group, $p < .05$. *T*-test comparisons for each age group compared against a baseline of an equal reliance on beginnings and endings indicated that the 5/6 year olds did not rely more on beginnings or endings, $t < 1$, $p > .7$, presumably because of the generally high number of first syllable responses by these children. However, the other three age groups demonstrated greater reliance on endings than beginnings, $t(53) = 4.83$, $t(54) = 7.59$, and $t(38) = 7.54$, for ages 7/8, 9/10, and 11/12, respectively, all $p < .001$. This relates to the greater reliability of endings over beginnings from the token corpus discriminant analyses. The type corpus analysis did not reveal a significant change in the relative reliability of beginnings versus endings, thus suggesting that children's responses are guided in part by the frequency of occurrence of beginning and ending cues with respect to stress position, and not only to the different types of occurrence of the cues.

INSERT FIGURE 4 HERE

A note on accuracy rates. We posit that the liberal coding method we have used here is appropriate method for a study concerned with stress assignment during the reading aloud of polysyllabic nonwords in English speaking children. Neither the corpus analysis in Study 1 nor the computational investigation to follow in Study 3 are concerned with the correlation between orthography and segmental phonology. Similarly, in Study 2 our focus was on suprasegmental phonology. We assert that children's productions provide valuable information about orthographic cues to stress assignment even when they are not, strictly speaking, acceptable approximations in terms of segmental phonology. In fact, it is an open empirical question as to whether segmental phonology is realized prior to, in combination with, or after suprasegmental phonology when reading aloud. In our data children's attempts at reading aloud the nonword "mabince" included responses such as "AMbince" (with clear first syllable stress, but reversal of the initial phonemes) and "maBWINCE" (with clear second syllable stress, but insertion of an additional phoneme). Phenomena such as phoneme reversal and phoneme insertion are well known features of children's productions. Our liberal coding method takes these pronunciations into account whereas a stricter method of coding might not.

However, it is valuable to be able to demonstrate that children were attending to the orthographic stimuli presented to them. One way to do this is to examine the segmental accuracy of children's responses. We calculated the overall accuracy rate for each of the four age groups and found that the percentage of acceptable approximations in terms of segmental phonology was: 44.6% for 5/6 year olds (remember only 7 children aged 5 years were included in our testing), 71.1% for 7/8 year olds, 88.9% for 9/10 year olds and 91.5% for the 11/12 year old children. These figures are comparable to a previous study of the reading aloud of bisyllabic nonwords in English speaking children. In that study, Goswami, Ziegler, Dalton, and Scheider (2003) were concerned with segmental phonology (stress assignment was not mentioned at all). Based on children's reading aloud of 16 bisyllabic words[2], Goswami et al. (2003) found accuracy rates of 51% for 7 year olds (n=24) and 82.3% for 8 year olds (n=24). It was reported that 95.3% of 9 year olds' (n=24) productions were accurate. For our data, we also calculated the percentage of responses that contained at least 50% of the target phonemes (e.g., thereby distinguishing close approximations such as "compoon" in response to the nonword "copoon" from a more distant approximation such as "adoosh" in response to the nonword "andet"). The data revealed that 85.5% of the responses by 5/6 children contained at least half of the target phonemes and this figure rose to 97.9% for 7/8 year olds, 99.5% in 9/10 year olds and 99.9% in 11/12 year olds. As one might expect,

[2] Note the number of bisyllabic nonwords that children were asked to read is comparable to the number of stimuli used in the current study. Children become fatigued when asked to read aloud polysyllabic nonwords and it is difficult to use large numbers of stimuli.

children's segmental accuracy increased with age, however, even from a very young age children appeared to be attending closely to the orthography of our nonword stimuli[3].

Summary of the results. Our behavioural study revealed a developmental trajectory regarding sensitivity to statistical cues for stress position, in line with the results of the corpus analyses reported in Study 1. The behavioural data also sheds light on the changing role of different regions of the word in guiding stress assignment. The corpus analyses show that word beginnings and endings provide useful cues to stress position, and also show the increasing reliability of word endings as a guide to stress position. The behavioural study shows that these properties are reflected in children's responses when they are learning to read. It may be that there is a salience to word extremes that guides reliance on this region of the word for providing stress position information.

To test whether a dynamic statistical learning system without bias to word beginnings and endings can discover the relative reliability of beginnings and endings, we tested a computational model of reading that learned to assign stress from written words in English. Specifically, we sought to determine whether a connectionist computational model would be sensitive to the same statistical properties of language that children appear to be, and whether a similar developmental profile in the model could be observed. The computational model can be viewed as another statistical method, but it enables a reflection of whether the children are learning only the statistical properties of the lexicon or whether their learning is driven by additional mechanisms, such as a word-

[3] A reviewer asked about whether we observed evidence of a serial sounding-out strategy when children were reading aloud. Sometimes a child sounded out 1 or 2 of the phonemes in a nonword at the beginning and/or the end of a nonword but this was mostly restricted to the very youngest age group. Part of the reason we did not see much evidence of sounding-out is that we tested only 7 children who were 5 years of age.

extreme bias. Additionally, in contrast to the discriminant analyses, the computational modeling enables us to test whether the relationship between orthographic cues and stress position can be discovered, rather than specifying the optimal solution as in the classical statistical methods. The computational modeling also enables us to plot a developmental trajectory – the discriminant analyses provide the solution for the beginnings/endings to stress position mapping, but does not provide insight into a computational system's *approach* to this solution.

In order to simulate the dynamic process of learning to read, we trained a computational model on corpora of age-appropriate words. At the first stage, the model was trained on words appropriate for 5 year old children. At the second stage, the model was exposed to the words appropriate to children's reading materials at age 6, and so on, up to the age of 12. Age was therefore operationalised in the model according to the age-appropriate set of words in the model's current training set.

Study 3: Modeling Stress Assignment

The computational model was trained on all bisyllabic words in English according to their frequency of occurrence in age-appropriate literature for children aged 5-12, and was required to predict from the orthographic input the stress position of the word. Critically, we wanted to determine whether the model could: (1) learn only from orthographic cues the stress position of the word; (2) demonstrate early in learning the same bias as young children in terms of assignment of first syllable stress to words and nonwords; and (3) reveal the developing dominance of word-endings as indicators of stress position. The model was trained in an incremental manner, to simulate the child's growing reading experience, of ever-increasing sets of words. We first exposed the model to a set of words appropriate for 5 year olds. After exposure to this word set, the model was then exposed to a set of words appropriate for 6 year olds, and so on, up to the age-12 word set. Age-appropriate word sets were determined from the WFG (Zeno et al., 1995), and exactly corresponded to the word sets tested in the corpus analyses reported in Study 1.

Method

Architecture. We constructed a supervised feedforward connectionist network that learned to map the orthography of words onto their stress position. Connectionist models provide a reflection of the statistics of the environment to which they are exposed. Furthermore, because they are trained iteratively, developmental trends in terms of their sensitivity to different aspects of the statistics of the environment can be determined. Connectionist models learn by adjusting the weights on connections between units to more closely approximate a target solution. Over time, these connection weights change so that the model's responses become more accurate. Initially, such models show sensitivity to the gross statistical generalities available in the environment (see, e.g., Yang, McCandliss, Shu, & Zevin, 2009). Later, connectionist models can learn more subtle statistical patterns. Connectionist models therefore provide an ideal mirror for determining the extent to which behavioural patterns in reading development are due to learning statistical regularities of increasing complexity from exposure to age-appropriate word sets. Such models do not contain any other assumptions of how learning progresses, and so the contribution of the statistical patterns in orthography-stress position mappings alone can be adjudged.

Computational models of reading typically instantiate slot-based representations of words, such that each letter fills one slot in the input, and words are thus represented as sets of adjacent slots in the input. Such computational models typically address only monosyllabic words, and tend to be vowel-centred in the input (e.g., Harm & Seidenberg, 1999, 2004), or undergo parsing (e.g., Perry et al., 2007) such that the onset, vowel, and coda are easily distinguished (and aligned) in the model's input. As we were interested in the relative roles of regularities in word beginnings and endings in stress assignment, we aimed to avoid biasing the model towards processing the statistics of either word beginnings or endings. At the same time, we had to ensure that the statistical regularities from beginnings and endings were available to the model. To ensure that beginning regularities were present in the model's input, we left-aligned words in the input, such that the first letter of each word was in the first slot, the second letter in the second slot, and so on. However, left-aligning words in the model's input would have meant that regularities in the ending were not reliably available to the model. Consider the words "typhoon" and "maroon". Left-aligning these words would have meant that the ending cue "-oon" occurred in letter slots 5, 6, and 7 for "typhoon", and in slots 4, 5, and 6 for "maroon". Our corpus analyses revealed that the ending "-oon" is a powerful cue for predicting second syllable stress in bisyllabic words, but the model can only discover this if the cue occurs in the same letter slots across words. Consequently, we also right-aligned words in the input, such that the final letter occurred in letter slot 14, the penultimate letter occurred in letter slot 13, and so on.

There were thus two orthographic input layers, composed of 14 letter slots each, to accommodate all bisyllabic words occurring in the WFG (Zeno et al., 1995). The first input layer contained a left-aligned representation of the word and the second contained a right-aligned version of the word. Thus, the potential influence of beginnings and endings on the model's performance was balanced. In each letter slot, one of 26 units was active to represent the letter, or for an empty slot none of the 26 units were active. The input layers were fully connected to a layer of 100 hidden units. This number of hidden units was found to be sufficient for mapping orthography to stress position for a large lexicon of English (Seva et al., 2009). The hidden units were, in turn, fully connected to one output stress unit (see Figure 5), where the model's decision about the stress position for the word could be determined. The output unit was trained to be inactive for first syllable stress and active for second syllable stress words. Before training, the weights on connections were set randomly in the range (-.5, .5).

In order to determine the effect of the left- and right-alignment of orthography in the model, we tested two additional models, one where words were only left-aligned, and another where words were only right-aligned. Comparing these additional models to the children's behavioural data enabled us to determine whether children present with initial biases to word beginnings or endings, or whether the behavioural patterns emerge from growing sensitivity to the statistics of the orthography-stress position relationship.

INSERT FIGURE 5 HERE

Training and testing. The model was trained incrementally with age-appropriate words taken from the WFG list in order to simulate the child's gradual exposure to reading materials of progressive difficulty and vocabulary size. Words were sampled randomly according to their frequency for presentation to the model. For each word, the orthographic form was presented at the input and the target stress position was presented at the output. The model was trained using the backpropagation learning algorithm, with sum square error calculated at the output unit as the error signal. For words with first-syllable stress, the stress unit's target activity was 0, for second syllable stress it was 1. We varied two parameters in the model to test whether its performance was robust. The first was the number of examples of each set of age-appropriate words, which we varied over 50,000, 100,000, and 200,000. We used 200,000 presentations as the maximum as in nearly all cases by this stage the model's performance was close to asymptote in accuracy of stress prediction. The second parameter we varied was the learning rate, which varied over .01, .001, and .0001.

The model was tested after being trained on each of the four age-appropriate word groups in succession. So, for each run of the model, the model first learned to assign stress for the age 5 words. Then, after the number of examples at that age had been presented (50, 100, or 200 thousand), the same model continued to be trained with age 6 words, and so on, up to the age of 12. The model was judged to have assigned first syllable stress if activation of the output unit was less than .5, and second syllable stress for activity greater than .5. At each stage of training, the model was tested on all the words in the age-appropriate set, and was also tested on the sets of nonwords from Study 2. The simulation was repeated twenty times, each with different randomized starting weights and different randomized order of presentations of words to the model. Each simulation run was entered as a subject in the analyses.

Results and Discussion

Left- and right-aligned model. The left- and right-aligned model's performance, under the different parameter settings, for accurately determining the stress position of all words in the training set at each age is shown in Figure 6.

Initially, under all parametrisations, there was a bias towards assigning words with first syllable stress, with increasing accuracy for second syllable words after more exposure to the later age-appropriate lexica. Higher learning rates, enabling the learning of the second-syllable stress "exception" words, resulted in greater accuracy in later stages of training, and, similarly, longer exposure to the words in each reading stage resulted in higher accuracy (particularly in terms of more second syllable responses to second syllable stressed words). Faster learning rates and longer exposure to each stage advanced the model's performance in terms of mastery of the word set at an earlier reading stage. However, all parametrisations indicated a qualitatively similar pattern of results. The model learned to assign stress to words in the training set to a high degree of accuracy, suggesting that the statistical cues in orthography were sufficient for good levels of classification of the lexicon, as in the corpus analyses. In addition, the model's performance on the second-syllable stressed words was initially lower than for first-syllable stressed words, but increased with age. Additional training on the set of words resulted in 99% accuracy (see Seva et al., 2009, for a model trained to 5 million patterns on all English bisyllabic words from the CELEX database).

INSERT FIGURES 6 AND 7 HERE

In order to compare the model's performance to the behavioural data reported in Study 2, we performed the same statistical analyses of the model's response at different "ages" for the nonwords. For each type of nonword, we performed a similar statistical analysis to that applied to the children's data in Study 2. We report the statistical analyses of the medial setting of the parameters – 100,000 example presentations at each age and learning rate of 0.001 – because this model showed accurate eventual performance on both first- and second-syllable stressed words, did not learn the second syllable nonwords too early in training, and performed at an intermediate level on the training set consistent with children's reading performance accuracy on words at each age.

Percentage of responses for the different nonword types are shown in Figure 7 for the model with this parameter setting. A 4 x 2 x 2 ANOVA was conducted with age group in terms of the age-appropriate corpus on which the model was being trained (5/6, 7/8, 9/10, 11/12), beginnings (whether nonword beginnings indicated first or second syllable stress), and endings (whether nonword endings indicated first or second syllable stress) all as within-subject variables. Age was a within-subject variable as the simulations could be treated as subjects in a longitudinal study – each simulation run was tested at all ages. The dependent variable was number of nonwords pronounced with first syllable stress. As with the behavioural results in Study 2, there was a significant main effect of age, $F(3, 57) = 104.33$, $p < .001$, $\eta^2 = .85$, with reducing proportion of first-syllable stress responses with age (from 78.1% of responses at ages 5-6, to 63.4% of responses at ages 11-12). There was a significant main effect of beginnings, $F(1, 19) = 776.31$, $p < .001$, $\eta^2 = .98$, with words with beginning cues indicating first syllable stress resulting in more first syllable responses than words with second syllable beginning cues (83.7% and 51.3%, respectively). There was also a significant main effect of endings, $F(1, 19) = 1158.86$, $p < .001$, $\eta^2 = .98$, with first-syllable endings resulting in first syllable responses 92.6% of the time, but 42.4% for second-syllable endings.

There was a significant interaction between age and beginnings, $F(3, 57) = 5.30$, $p < .005$, $\eta^2 = .22$. This was due to an overall reduction to first syllable responses but a quicker reduction to second-syllable beginning nonwords in the intermediate ages (at age 5/6 95.9% responses to first-syllable beginning nonwords compared to 60.3% for second-syllable nonwords; and by age 11/12: 77.9% to first-syllable beginnings, and 48.9% to second-syllable beginnings). There was also a significant interaction between age and endings which reflected the behavioural results from Study 2, $F(3, 57) = 64.93$, $p < .001$, $\eta^2 = .77$, with an initial smaller effect of first-/second-syllable endings on first-syllable responses at age 5/6 (95.9% versus 60.3%), and later a greater effect at age 11-12 (91.5% and 35.3% for first- and second-syllable ending nonwords, respectively). The interaction between beginnings and endings was significant, $F(1, 19) = 225.86$, $p < .001$, $\eta^2 = .92$, with the largest number of second syllable responses to nonwords with beginning and ending cues that indicated second syllable stress (17.4%), compared to when just beginnings or endings indicated second syllable stress (85.1% and 67.5%, respectively). The three-way interaction was also significant, $F(3, 57) = 30.41$, $p < .001$, $\eta^2 = .62$.

The significant effects revealed in the behavioural study were also significant in the left- and right-aligned computational model's performance. The model was sensitive to both beginnings and endings of the nonwords in terms of determining the stress position. Furthermore, the interactions indicated that this sensitivity increased with age, similar to the developmental data of Study 2. The model's performance differed from Study 2, however, in that the proportion of second syllable stress responses given by the model was lower than that given by the children, at all ages. This was due to the large proportion of first-syllable stressed words in the model's training environment. Only 18% of bisyllabic words in the age 5/6 lexicon had second syllable stress, and the model reflected this to a certain extent early in training in terms of stress assignments for the words and the set of nonwords.

Our requirement for activation to be greater than .5 at the model's output unit in order to demonstrate second syllable stress was a conservative measure to describe second syllable stress judgment, and a weaker criterion results in a greater proportion of second syllable stress responses. We reanalyzed the model's performance using a weaker criterion for second syllable response. As second syllable words comprise approximately 18% of the word sets at each age, if the model was responding purely by matching to the probability of the training set, then default activation should be .18. Thus, an activation in the model of less than .18 indicates a judgment about stress position being on the first syllable and greater than .18 indicating a judgment of second syllable stress. For this more lax criterion for second syllable stress response, the model produced a greater number of second syllable responses, but the general patterns of results were the same as for the original stricter cut-off criterion of .5.

For the entire training set, by age 12, the left- and right-aligned model assessed with the .18 cut-off criterion was accurate for 83.6% ($SD = 1.5$) of first syllable stress and 83.2% ($SD = 1.4$) of second syllable stress words. For the 4 x 2 x 2 ANOVA with age group, beginning cue, and ending cue as factors, there were main effects of age, $F(3, 57)$

= 3.41, $p < .05$, $\eta^2 = .15$, a significant main effect of beginnings, $F(1, 19) = 739.22$, $p < .001$, $\eta^2 = .98$, a main effect of endings, $F(1, 19) = 1502.58$, $p < .001$, $\eta^2 = .99$, an interaction between age and beginnings, $F(3, 57) = 6.92$, $p < .001$, $\eta^2 = .27$, an interaction between age and endings, $F(3, 57) = 6.92$, $p < .001$, $\eta^2 = .27$, a significant interaction between beginnings and endings, $F(1, 19) = 41.58$, $p < .001$, $\eta^2 = .67$, and a significant three-way interaction, $F(3, 57) = 3.41$, $p < .05$, $\eta^2 = .15$. As for the behavioural data, and for the initial modeling results, the role of endings in determining stress assignment increased with age. The less stringent cut-off criterion also resulted in a greater number of second syllable stress responses by the model. For the nonwords with consistent beginning and ending cues to second syllable stress, the model responded 100% of the time with a second syllable stress judgment for all age groups, which demonstrates that the model can be interpreted to learn to respond frequently to second syllable stress words and nonwords.

As with the behavioural data in Study 2, we required an explicit test of whether the left- and right-aligned model was more reliant on beginnings or endings. Hence, we performed an analysis only on the nonwords with inconsistent beginnings and endings, similar again to the analysis in the behavioural Study 2, with the original cut-off of .5 to distinguish between first and second syllable responses. The dependent variable was the proportion of nonwords assigned stress according to the beginning cue, and age group was the independent variable. The results are shown in Figure 8. As with the behavioural data shown in Figure 4, values greater than .5 indicate that responses were more often in accordance with the statistical distributions of the beginning cues, whereas values lower than .5 indicate greater reliance on the ending cues. There was a main effect of age, F(3,

57) = 37.41, p < .001, η^2 = .66, indicating that the influence of beginnings reduced with age in the model. The results are again consistent with the behavioural data from Study 2 in terms of the growing reliance on ending cue as age increases, though the overall proportion of second-syllable responses meant that the biases in responses to one or other cue were reduced in the model compared to the behavioural data.

INSERT FIGURE 8 HERE

Left-aligned model versus right-aligned model. The performance of the left-aligned model versus the right-aligned model was tested with the same parametrisation as the left- and right-aligned model. After 100,000 patterns of training at each age-appropriate reading stage the left-aligned model produced correct stress for a mean 95.7% (SD = .3) of the first-syllable stressed words and 49.2% (SD = 1.6) of the second syllable stressed words. The right-aligned model produced correct stress for 96.0% (SD = .1) and 35.2% (SD = 1.4) of the first- and second-syllable stressed words, respectively.

The same 4 x 2 x 2 ANOVA as was applied to the left- and right-aligned model was conducted on number of nonwords pronounced with first syllable stress, with age, beginnings, and endings as within-subject variables for the two new models. The results were qualitatively similar to those of the left- and right-aligned model, and are shown in Table 4. Of note, although the left-alignment was biased to beginnings, the effect of endings was still available to the model as occasional overlaps between similar endings fall on the same slots in the input (though "typhoon" and "maroon" are misaligned at the ending, "maroon" and "cocoon" still share an ending cue). Similarly, for the right-aligned model, sensitivity to the regularities in beginnings was present, but, as anticipated, there was a larger effect of endings.

INSERT TABLE 4 HERE

As before, for the ANOVA on only the nonwords with inconsistent beginnings and endings, the dependent variable was the proportion of nonwords assigned stress according to the beginning cue, and age group was the independent variable. For the left-aligned model, there was a main effect of age, $F(3, 57) = 17.55$, $p < .001$, $\eta^2 = .48$, though there was no regular increase in responses according to ending cues as in the behavioural study and in the left- and right-aligned model (see Figure 8). For the right-aligned model there was a significant main effect of age, $F(3, 57) = 43.94$, $p < .001$, $\eta^2 = .70$, with increasing age relating to more use of ending cues over beginning cues, as with the behavioural data and the left- and right-aligned model (see Figure 8), however, the proportion of reliance on ending cues was reduced slightly in comparison to the left- and right-aligned model. Figure 8 demonstrates that the children's developmental data is most closely simulated by a model that computes a combination of beginnings and endings cues.

Summary of results. Overall, the simulation results indicated that the computational model was able to learn the stress position of words and nonwords in English from orthography. In addition, early in training on realistic corpora of age-appropriate written language, the model was sensitive to the same biases as young children, both in terms of assignment of first syllable stress to words and nonwords and for the developing dominance of word-endings as indicators of stress position. The modeling suggests that the statistical properties of the lexicon alone can result in learned biases to word extremes as orthographic indicators of stress position, and an increasing dominance of word endings[4].

Comparison of the performance of the left-aligned model and the right-aligned model with the left- and right-aligned model, demonstrated that a balanced combination of both beginning and ending cues was necessary for reflecting the behavioural data. When the model was biased to beginning cues, the growing reliance on ending cues with age was not found. When the model was biased to ending cues, the model did not produce sufficient second-syllable responses for the consistent second syllable cue nonwords to reflect the children's data. Taken together, these results suggest that children do not present with an initial bias to word beginnings or endings. Rather, the model that balanced information availability from beginnings and endings equally in contributing to stress assignment best matched to the children's developmental data. In this model, and in the children's pronunciations, when ending cues are available these become increasingly potent in guiding stress assignment.

No other mechanisms in the left- and right-aligned model, other than sensitivity to the statistical properties of the mapping, were required to generate this pattern. However, there is evidence that other cues do contribute to stress assignment. Arciuli and Cupples

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[4] A reviewer pointed out the increasing influence of endings may not due to the increasing reliability of endings in determining stress position in age-appropriate corpora, but due to the model learning with time to utilize the ending cue. We tested this in an additional simulation which was trained only on the age 5-6 corpora with the same parametrisation as the other models. At the end of training it showed good performance for first syllable stress words but poorer performance on second syllable stress words. Interestingly, the model did show an increasing reliance on endings compared to beginnings as training advanced. Thus, an adequate model for simulating human reading development requires exposure to age-based corpora in order to learn stress assignment accurately, but the increasing reliance on endings is, at least in part, a consequence of extended training.

(2006) demonstrated that grammatical category, for instance, is also an important factor for predicting stress position. It is plausible that, as children learn about their language, additional cues such as grammatical category could also be available for deciding on stress assignment. Our focus in all three studies in this paper has been on the extent to which orthographic regularities can predict stress assignment during reading development, but the issue of how and when additional cues (such as grammatical category) may become available to the learning reader is an important issue for future research.

General Discussion

To date, models of reading have typically focused on monosyllabic words (e.g., Coltheart et al., 2001; Harm & Seidenberg, 2004; Perry et al., 2007; Seidenberg & McClelland, 1989). Great gains have been made in understanding the process of mapping between graphemes and phonemes. However, there are important aspects of reading that only come into play when processing polysyllables, in particular, issues concerning the assignment of lexical stress and its developmental trajectory, which have not yet been adequately addressed.

A comprehensive understanding of stress assignment during reading aloud of polysyllables is essential for providing enriched insight into the cognitive processes of reading, particularly given that the majority of word types are polysyllabic in English (90.8% of word types in CELEX). In languages such as English, patterns of lexical stress are variable (i.e., not predictable in a straightforward way as in languages with fixed patterns of stress). There is research to suggest a rich source of probabilistic orthographic cues to guide lexical stress in adult lexica – that can be derived without recourse to morphologically derived affixes (see Arciuli & Cupples, 2006; 2007). Several studies have now demonstrated that these cues are present in the beginnings and endings of words and that adults are sensitive to these cues (Arciuli & Cupples, 2006; 2007; Kelly, 2004; Kelly et al., 1998). However, there has been no investigation of the relative contribution of beginnings versus endings as cues during stress assignment, no investigation of the presence of such cues in child lexica, and no investigation of children's sensitivity to these cues during the early years of reading. In the current study we addressed three key issues:

1. The extent to which the beginnings and/or the ends of words (in terms of orthography) predict stress placement in English in children's age-appropriate reading materials;

2. Children's sensitivity to orthographic cues to stress in their reading aloud of nonwords; and

3. Whether a computational model that learns the statistical consistencies between orthography and stress position is sensitive to words' beginnings and endings in the same way as children.

Our corpus analyses indicated that, for age-appropriate lexica, there is substantial information in the letters at the beginning and ending of the word to determine stress assignment with a high degree of accuracy. With increasing age, the relative advantage of endings compared to beginnings as determinants of stress becomes greater. The behavioural study demonstrated that children are sensitive to these statistical properties of English. As children have more practice in reading, they lose an initial bias to pronounce unfamiliar words with first syllable stress, and become more attuned to word endings in guiding their decisions about pronunciation.

While some previous behavioural studies have examined the link between children's sensitivity to lexical stress and overall reading ability (e.g., Jarmulowicz, Hay, Taran & Ethington, 2008; Gutierrez-Palma & Reyes, 2007), others have begun to examine the specific mechanisms responsible for assigning stress during the reading aloud of polysyllables in languages such as Greek (e.g., in Greek as in Protopapas, 2006; Protopapas et al., 2006; Protopapas & Gerakaki, 2009). We are not aware of any previous studies that have attempted to discover the developmental trajectory of stress assignment during reading aloud in English or any that have used a triangulation of corpus analyses, behavioural data and computational modeling to learn about children's polysyllabic word reading. Our results suggest that stress is assigned based on sensitivity to statistical probabilities that are present in written input and that this sensitivity follows a developmental trajectory.

Our computational model trained to map orthography onto stress position for bisyllabic words indicated qualitatively similar performance to children learning to read. Initially, the first-syllable stress bias was found, but with age there was an increasing dependency on word endings in guiding pronunciation. Our modeling indicated that learning the statistical properties of the lexicon resulted in the same stress-assignment effects found in reading development. An additional model trained only on age 5-6 corpora (see Footnote 4) indicated that the increasing reliance on endings is, at least in part, a consequence of extended training. Thus, word endings may rather serendipitously provide information where it is most used by the developing reader.

Importantly, the computational model we have presented does not have a lexical component for stress assignment. The lexical level is potentially available, as all letters within the word are inputted to the model simultaneously, yet the accurate encoding of stress by the model is not due to access to a specified lexicon. Nonmorphologically derived parts of a word can provide valuable information about stress without recourse to lexical level representations. Furthermore, assignment of stress for nonwords appears to be based on the same sublexical information that we determined to be highly accurate for assigning stress in real words. Thus, although we cannot categorically rule out that stress is stored in a lexicon, we contend that sublexical information is sufficient to solve the task of stress assignment. Independent proof is required to show that this sublexical information is disregarded in the process of word naming.

Our model suggests instead that sublexical properties of words drive their pronunciation (see also Seva et al., 2009, for more discussion of this issue). It is likely that morphological cues still play an important role in stress assignment, though they are not sufficient to determine stress assignment due to the large number of words that are monomorphemic. The corpus analyses of the whole lexicon and the monomorphemic subset provide a means of estimating the relative role of non-morphological orthographic cues and morphologically-based orthographic cues. For the token analyses (Figures 1a and 2a), the difference in classification accuracy between the whole corpus and the monomorphemic corpus is minimal, though classification accuracies based on a smaller set of words are likely to be more accurate, as chance level classification levels are also slightly elevated. For the type analyses, the role of morphology is apparent, with a reduction of accuracy for the monomorphemic analyses of up to 4.1% for the 11-12 year lexicon. Interestingly, the classifications based on beginnings are most affected by the removal of morphology (dropping 8.0% for age 11-12, compared to a 1.6% drop for endings, see Figures 1b and 2b), providing some support for the decision in the Rastle and Coltheart (2000) model to concentrate on word-initial morphology for contributing to stress assignment.

The model provides insight into only one aspect of pronunciation of polysyllabic words – that of stress assignment – but as such it indicates that assumptions made for models of monosyllabic words do not generalize adequately to the entire lexicon, which is primarily composed of polysyllables. A notable absence from the current model is the mapping from orthography to segmental phonology, which is necessary for providing a full account of polysyllabic word reading (e.g., Ans, Carbonnel, & Valdois, 1998). Data and models of polysyllabic word reading are surprisingly sparse, particularly given the large proportion of the lexicon that is polysyllabic (though see Jared & Seidenberg, 1990, and Taft, 1992). Recent research by Yap and Balota (2009), Kello (2006) and Perry, Ziegler, & Zorzi, (2008) have begun to explore how methods and principles involved in monosyllabic reading can be extended to polysyllabic models. The results of our studies provide important constraints for the representations and processes in such models. We have shown that the word's ending has an important role in pronunciation, consistent with Jared and Seidenberg (1990). In terms of generating the segmental phonology of a word, Chateau and Jared (2003) found that the consistency of pronunciation of the BOB (the vowel plus following consonants up to the next vowel) of the first syllable as well as the identity of the second vowel both predicted word naming latencies. Whereas, Yap and Balota (2009) found that the consistency of the pronunciation of both the onset and rime of both syllables contributed to variance in word naming response time and accuracies. It would be valuable to determine whether the same regions of the beginning and ending of the word are similarly useful for driving segmental and suprasegmental phonology.

The corpus analysis, behavioural, and modeling results present challenges to current models of reading that posit serial encoding of letters in words in order to generate pronunciation. Dual-route models of reading (e.g., Coltheart et al., 2001) and more recent manifestations (e.g., Perry et al., 2007) propose that graphemes are processed serially from left to right. Yet, the growing reliance on endings for stress assignment as children grow older requires that processing of the right portion of the word is required before pronunciation can proceed. Indeed the end of the word provides the greatest contribution as a cue to stress assignment for the older children, and for the simulations of older reading environments in the computational model. Adequate models of detailed developmental reading data, then, require processing of both extremities of the word with respect to stress to occur before pronunciation (see Seva et al., 2009, for further discussion on this point). As our modeling indicates aligning words at only the beginning or only the ending resulted in poorer simulation of children's reading development than the left- and right-aligned model. Providing availability of regularities at both extremes of the word seemed to be critical for reflecting orthography-stress regularities. We utilized a slot-based coding scheme which has limitations, particularly for permitting the regularities in the inputs to be discovered by the model. However, the slot-based approach is not critical to our model. We envisage even more effective models that incorporate more flexible representations of the order of letters in words, such as open bigrams or spatial coding (see Davis & Bowers, 2006, for a review).

Incorporating segmental phonology into our model may improve stress assignment performance further, as predicted by Chomsky and Halle (1968). Rastle and Coltheart's (2000) rule-based model of stress, for instance, bases its decision in part on the pronunciation of the vowel which contributes substantially to accurate performance. Segmental phonology may be an important additional cue in stress assignment, as children have substantial experience of pronouncing words before they begin exposure to written forms. Correspondences between certain patterns of phonemes and stress positions are likely to improve performance further. However, incorporating such pre-training into the model requires decisions to be made about whether construction of prosodic structure occurs before or in tandem with or after construction of segmental phonology (e.g., Levelt, Roelofs, & Meyer, 1999), and different decisions will lead to alternative predictions about the relative role of pre-exposure to phoneme-stress regularities in the child's vocabulary.

We contend that adequate models of reading must be extended to accommodate data on the developmental aspects of polysyllabic reading, from their current base of monosyllabic reading. In this respect, the triangulation of corpus, behavioural, and computational modeling techniques within this paper illustrate how an integrative approach to profiling the child's language environment can provide insights into the sources of information available to, and used by, the child during reading aloud.

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Captions for tables and figures

Table 1. Number of distinct beginnings and endings.

Table 2. Corpus size for bisyllabic words in WFG for each age group.

Table 3. List of nonwords with cues to stress in beginnings and endings.

Table 4. ANOVA results for the left-aligned and right-aligned models.

Figure 1. Results of discriminant analyses of age-appropriate texts showing the percentage of words correctly classified as having either first- and second-syllable stressed words on the basis of beginnings or endings. (A) token (frequency-weighted) analysis, (B) type analysis (no frequency weighting).

Figure 2. Results of discriminant analyses of only the monomorphemic words contained within age-appropriate texts showing the percentage of words correctly classified as having either first- and second-syllable stressed words on the basis of beginnings or endings. (A) token analysis, (B) type analysis.

Figure 3. Percentage of responses of each type for nonwords with beginning and ending cues indicating first or second syllable stress position, separated by age group. (A) first-

first nonwords; (B) first-second nonwords; (C) second-first nonwords; (D) second-second nonwords.

Figure 4. Reliance on beginnings or endings for nonwords with inconsistent cues for each age group. Values lower than .5 indicate more reliance on endings.

Figure 5. The connectionist model of stress assignment from orthography. Arrows indicate connections between layers. The input shows two banks of units, representing the left- and right-aligned words, and stress position was represented in terms of different activity at the output unit.

Figure 6. Performance of the left- and right-aligned model with different parameter settings on accurate stress assignment for first- and second-syllable words in the training set at different ages. Different markers on the lines indicate the number of examples of words presented at each age. The shading of the line indicates the learning rate (light grey = low learning rate, dark grey = medial learning rate, black = high learning rate). The solid lines indicate performance for models trained with different parameters on the first-syllable stressed words, and the dashed lines indicate performance on the second-syllable stressed words.

Figure 7. Left- and right-aligned model's percentage of first-syllable stress assignment for nonwords with beginning and ending cues indicating first or second syllable stress

position, separated by age group. (A) first-first nonwords; (B) first-second nonwords; (C) second-first nonwords; (D) second-second nonwords.

Figure 8. Reliance on beginnings or endings for nonwords with inconsistent cues for each age group for the left- and right-aligned model of stress assignment, also for the left-aligned and the right-aligned models, and shown with the children's data from Study 2. Values lower than .5 indicate more reliance on endings.

Table 1.

	All Words		Monomorphemic Words	
	Number of Beginnings	Number of Endings	Number of Beginnings	Number of Endings
5 years	34	116	22	33
6 years	43	166	26	44
7 years	44	211	26	57
8 years	44	260	26	60
9 years	47	294	27	69
10 years	47	319	29	72
11 years	49	322	30	75
12 years	47	329	30	77

Table 2.

Age	Total Number of Bisyllabic Words	Percentage of Bisyllabic Words Classed as Monomorphemic in Celex	Percentage of All Bisyllabic Words with each Stress Pattern (% of Monomorphemic Bisyllabic Words in Parentheses)	
			1st syllable stress	2nd syllable stress
5/6	2959	15.5	89.0 (88.1)	11.0 (11.9)
7/8	3814	21.4	85.9 (85.9)	14.1 (14.1)
9/10	4430	20.6	83.6 (85.4)	16.4 (14.6)
11/12	4594	20.2	82.7 (83.7)	17.3 (16.3)

Table 3.

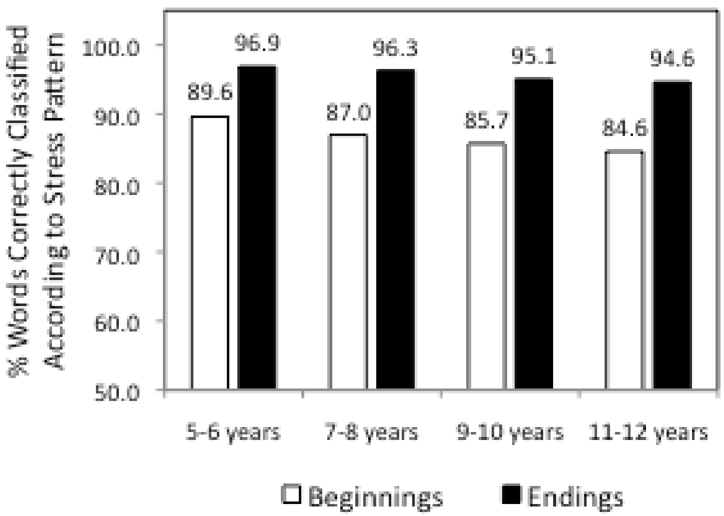
Consistent Cues		Inconsistent Cues	
Beg: 1st syllable stress End: 1st syllable stress	Beg: 2nd syllable stress End: 2nd syllable stress	Beg: 1st syllable stress End: 2nd syllable stress	Beg: 2nd syllable stress End: 1st syllable stress
mandol	bedoon	copoon	beppet
mapet	bemade	mapade	ambol
coddol	apoon	comade	andet
combet	abade	madoon	bendol
mambey	bedince	mabince	beddan
condan	adact	codact	ambey

Table 4.

Model	Effect	*F*	*p*	η^2
Left-aligned	Age	43.21	.001	.70
	Beginning Cue	1826.04	.001	.99
	Ending Cue	821.40	.001	.98
	Age x Beg	4.78	.005	.20
	Age x End	16.95	.001	.47
	Beg x End	146.27	.001	.89
	Age x Beg x End	6.59	.001	.26
Right-aligned	Age	205.76	.001	.92
	Beginning Cue	68.22	.001	.78
	Ending Cue	862.26	.001	.98
	Age x Beg	5.81	.005	.23
	Age x End	38.43	.001	.67
	Beg x End	104.96	.001	.85
	Age x Beg x End	162.62	.001	.90

Figure 1.

A


% Words Correctly Classified According to Stress Pattern
100.0
90.0
80.0
70.0
60.0
50.0
89.6
96.9
87.0
96.3
85.7
95.1
84.6
94.6
5-6 years
7-8 years
9-10 years
11-12 years
Beginnings
Endings

B

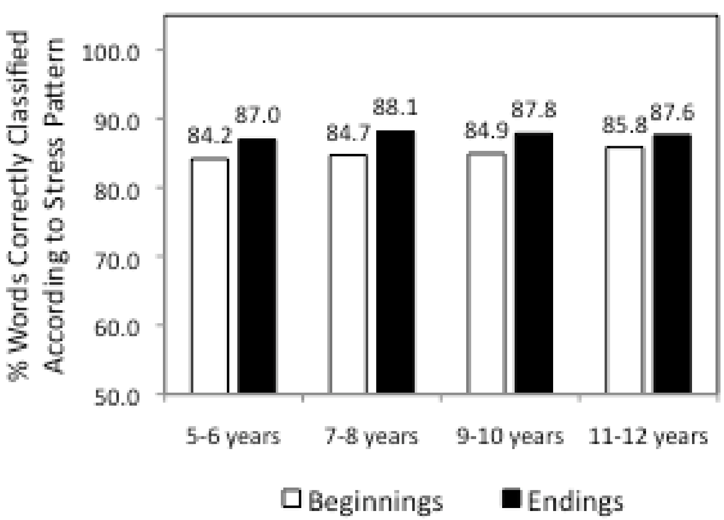
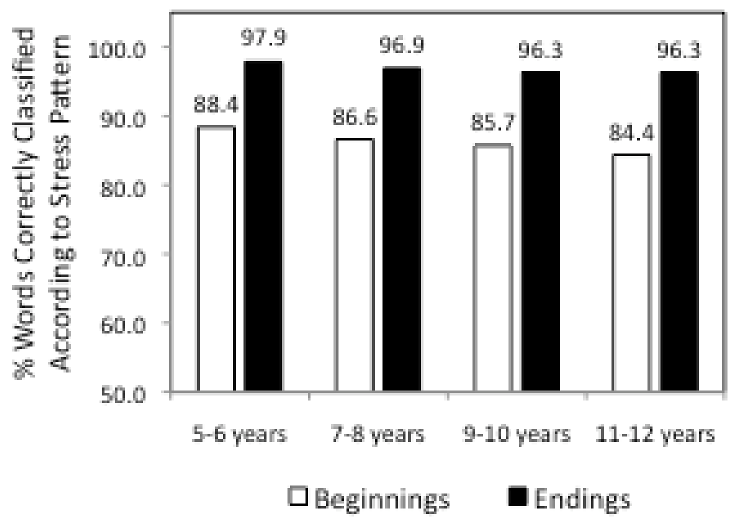

% Words Correctly Classified According to Stress Pattern
100.0
90.0
80.0
70.0
60.0
50.0
84.2
87.0
84.7
88.1
84.9
87.8
85.8
87.6
5-6 years
7-8 years
9-10 years
11-12 years
Beginnings
Endings

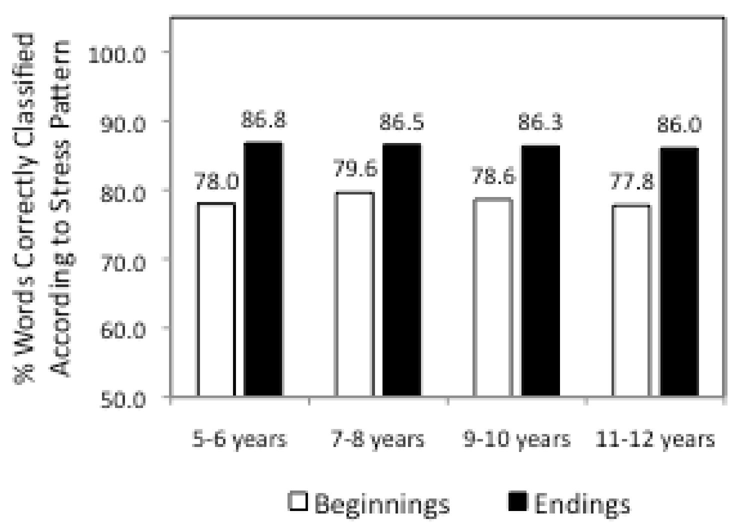
Figure 2.

A



% Words Correctly Classified According to Stress Pattern
100.0
90.0
80.0
70.0
60.0
50.0
88.4
97.9
86.6
96.9
85.7
96.3
84.4
96.3
5-6 years
7-8 years
9-10 years
11-12 years
Beginnings
Endings

B



% Words Correctly Classified According to Stress Pattern
100.0
90.0
80.0
70.0
60.0
50.0
78.0
86.8
79.6
86.5
78.6
86.3
77.8
86.0
5-6 years
7-8 years
9-10 years
11-12 years
Beginnings
Endings

Figure 3.

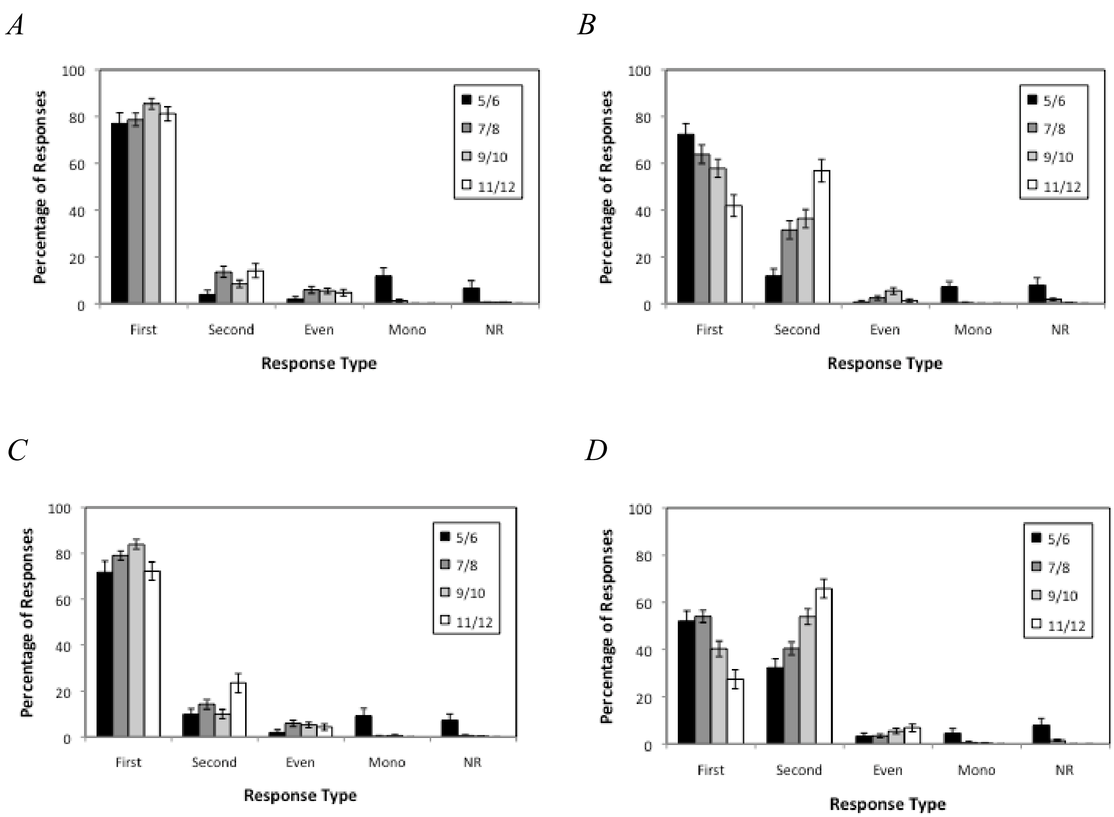
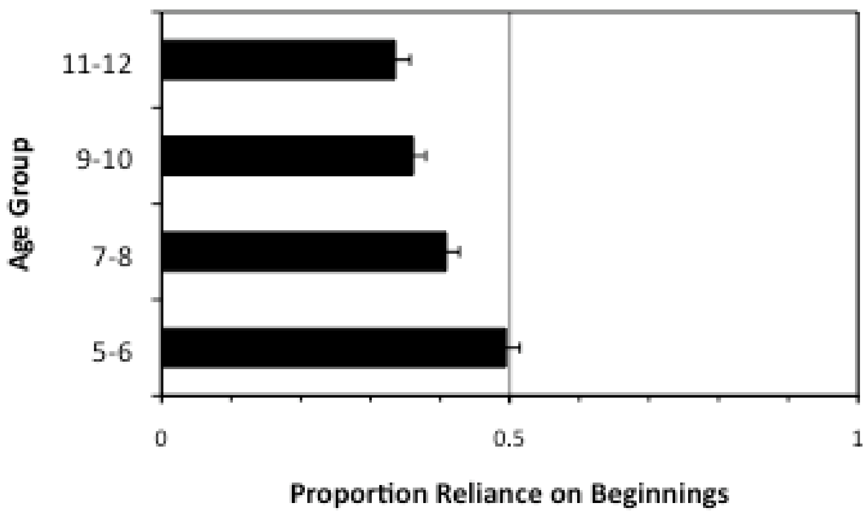

A
B
C
D
Percentage of Responses
0
20
40
60
80
100
First
Second
Even
Mono
NR
Response Type
5/6
7/8
9/10
11/12

Figure 4.



Age Group
11-12
9-10
7-8
5-6
0
0.5
1
Proportion Reliance on Beginnings

Figure 5.

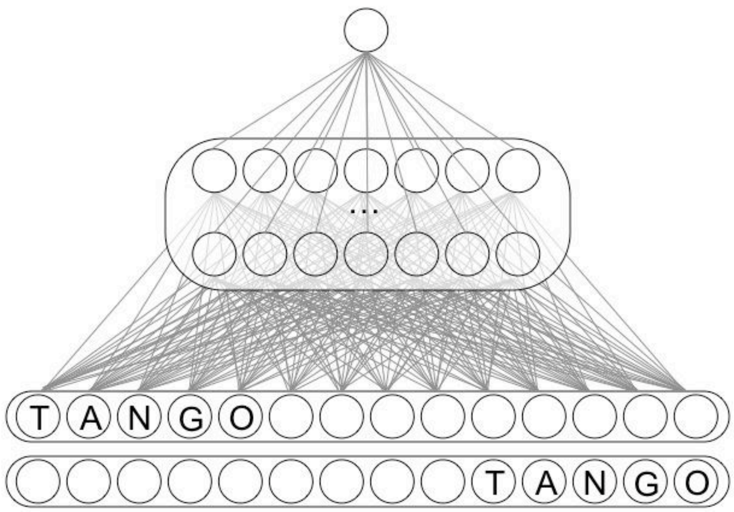


Figure 6.

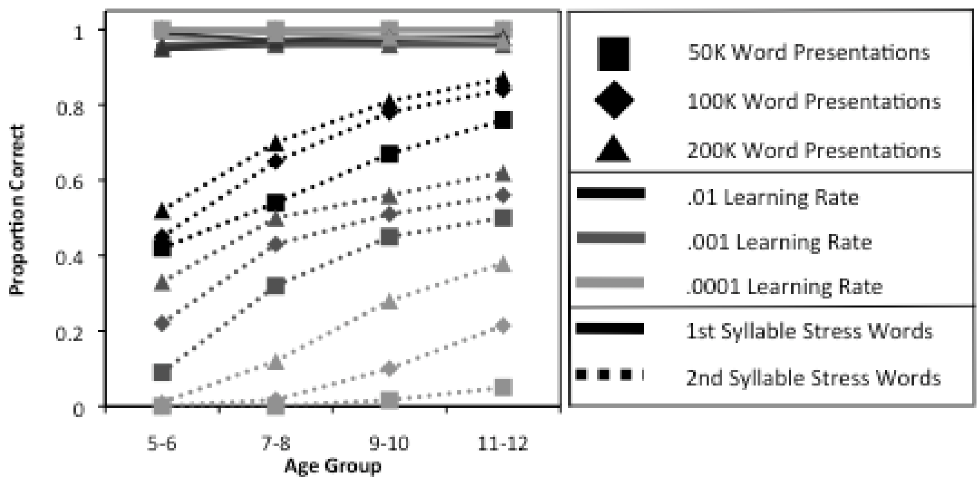

1
0.8
0.6
0.4
0.2
0
Proportion Correct
5-6
7-8
9-10
11-12
Age Group
50K Word Presentations
100K Word Presentations
200K Word Presentations
.01 Learning Rate
.001 Learning Rate
.0001 Learning Rate
1st Syllable Stress Words
2nd Syllable Stress Words

Figure 7.

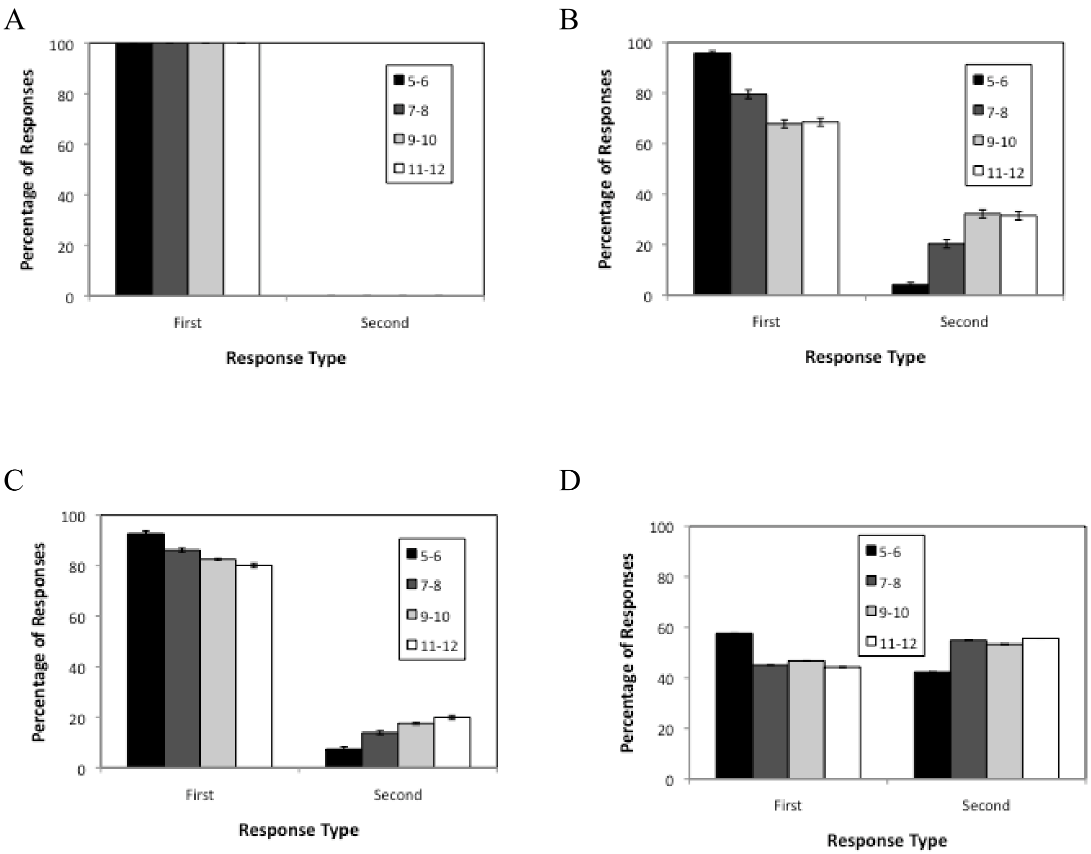
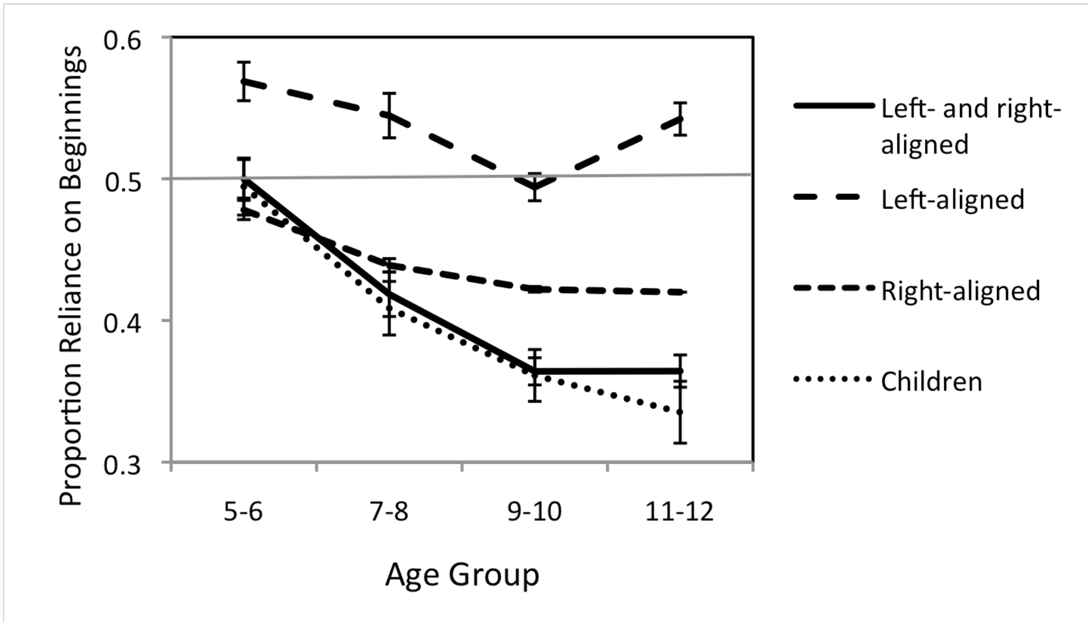

A
B
C
D
Percentage of Responses
Response Type
First
Second
0
20
40
60
80
100
5-6
7-8
9-10
11-12

Figure 8.



0.6
0.5
0.4
0.3
Proportion Reliance on Beginnings
5-6
7-8
9-10
11-12
Age Group
Left- and right-aligned
Left-aligned
Right-aligned
Children