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Children's Reading of Sublexical Units in Years Three to Five: A Combined Analysis of Eye-Movements and Voice Recording

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ABSTRACT

Purpose: Children progress from making grapheme–phoneme connections to making grapho-syllabic connections before whole-word connections during reading development (Ehri, 2005a). More is known about the development of grapheme–phoneme connections than is known about grapho-syllabic connections. Therefore, we explored the trajectory of syllable use in English developing readers during oral reading.

Method: Fifty-one English-speaking children (mean age: 8.9 years, 55% females, 88% monolinguals) in year groups three, four, and five read aloud sentences with an embedded target word, while their eye movements and voices were recorded. The targets contained six letters and were either one or two syllables.

Result: Children in grade five had shorter gaze duration, shorter articulation duration, and larger spatial eye-voice span (EVS) than children in grade four. Children in grades three and four did not significantly differ on these measures. A syllable number effect was found for gaze duration but not for articulation duration and spatial EVS. Interestingly, one-syllable words took longer to process compared to two-syllable words, suggesting that more syllables may not always signify greater processing difficulty.

Conclusion: Overall, children are sensitive to sublexical reading units; however, due to sample and stimuli limitations, these findings should be interpreted with caution and further research conducted.

Introduction

Learning to read involves making connections between the sounds and symbols of a language. Although reading development depends on language development (Nation & Snowling, 2004), the mechanisms underlying both are different. While children develop their language skills by exposure to a language-rich environment (Castles et al., 2018), reading develops primarily through direct instruction (Joo et al., 2021). The English Language National Curriculum is structured so children's word identification processes are trained to be fluent, with small units being introduced before large units (Department for Education, 2013). Word processing times increase with word length in German (Huestegge et al., 2009), Italian (Zoccolotti et al., 2008) and English (Hyona & Olson, 1995, Joseph et al., 2009) languages. Moreover, this effect is larger in younger children compared to older children and adults (Blythe et al., 2011, Joseph et al., 2009), suggesting a transition from using small orthographic units such as letters to larger units such as syllables, morphemes, or words as reading skill develops (Bruck & Treiman, 1992, Ziegler & Goswami, 2005). Again, this transition is highlighted early in children's education with explicit syllable instruction to aid the parsing of long words

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(Department for Education, 2013). Thus, allowing children to use preexisting words of shorter length in reading long words with more than one syllable without resorting to letter-by-letter decoding.

The developmental trajectory of syllable use during word recognition in Spanish, German, Portuguese, and French has been documented using behavioral data (Alvarez et al., 2016, Campos et al., 2021, Colé et al., 1999, Hasenäcker & Schroeder, 2016). While a number of studies have examined the awareness of intra-syllabic units such as onsets and rimes in English (Bruck & Treiman, 1992, Bruck et al., 1995, Treiman et al., 1995), very few studies have examined syllable development. Syllables play an important role as they encode information about words' pronunciation (Hasenäcker & Schroeder, 2016). Pronounciation is especially important during early reading instruction as children first learn to read aloud (Rasinski & Hoffman, 2003, Rayner et al., 2013). Interestingly, some evidence has suggested that eye-movements during oral reading in beginning readers (age 6) are more strongly related to reading ability compared to eye-movements during silent reading (Kim et al., 2019). Therefore, it is surprising that developmental studies examining syllable processing during oral sentence reading are sparse (but see Juel & Holmes, 1981) and limited to single-word paradigms. Consequently, the current study aimed to address this by investigating syllable representations in children from years three to five using simultaneous eye movement and voice recordings.

Reading development and syllable units

Ehri's (2005b, 2017) reading development model proposes that once children attain alphabetic knowledge-learning letters and their sounds, they progress to making grapho-syllabic connections. Reading instruction encourages children to make a transition from encoding individual letters to encoding larger grain size units, such as affixes, root words, syllables, morphemes, and words. Presentation of words with similar patterns reinforces these larger units and helps children develop consolidated units of recognition (Ehri, 2005a, 2005b, 2017). These consolidated units reduce memory load and improve fluency, allowing texts to be read more efficiently (Ehri, 2005a). For example, the word *purple* would be encoded as two syllabic units (*pur-ple*) rather than six letter units (*p-u-r-p-l-e*). Whilst familiar words with more than one syllable could be read as whole units, the predominant connections at this final consolidated alphabetic phase are grapho-syllabic or grapho-morphemic in nature (Ehri, 2005a, 2005b, 2017). Thus, readers may decode the pronunciation of newly encountered words using syllables.

Skilled readers show evidence of syllable encoding during word recognition. Readers take a longer time to process (Pelczarski et al., 2019), begin pronunciation of (Ferrand & New, 2003, Jared & Seidenberg, 1990, New et al., 2006, Yap & Balota, 2009) and make lexical decisions (New et al., 2006, Stenneken et al., 2007) on words or non-words with more syllables compared to those with fewer syllables. However, this inhibitory trend has been contradicted by evidence of null effects (Ashby & Clifton, 2005, Drieghe et al., 2019, Fitzsimmons & Drieghe, 2011, Frederiksen & Kroll, 1976) and facilitatory effects where words with fewer syllables may take longer to name (Lee, 2001). Syllable effects may also occur before a word is fixated. That is, readers may be able to extract phonological information in the form of syllables in the parafovea (Ashby, 2010, Ashby & Martin, 2008, Ashby & Rayner, 2004). Again, this pre-lexical finding is not without controversy (Drieghe et al., 2019). Interestingly, most of this conflicting evidence on syllable number effects has come mainly from English language, where syllable boundaries are less well defined (Cutler et al., 1986, Kahn, 1976, Seymour et al., 2003). Nevertheless, other experimental manipulations of syllable processing, such as syllable frequency effects, have shown that English readers have access to syllable representations like other languages with simple syllable structures and well-defined syllable boundaries (Spanish: Carreiras et al., 2005; German: Hutzler et al., 2005; English: Macizo & Van Petten, 2006).

Explanations for the use of syllable units have been provided by computational models of polysyllabic word recognition, which account for syllable number effects, namely the Multiple Memory Trace Model (MTMM; Ans et al., 1998) and Connectionist Dual Processing (CDP++; Perry et al., 2010) Model. The MTMM assumes that words are processed via two sequential routes: the global and analytical routes. Words are processed as whole units in the global route. However, processing via the analytical route depends on detecting a vocalic grapheme or nucleus which narrows the processing unit to the largest initial component or syllable recognized as familiar. The MTMM predicts that naming latency of pseudowords (for skilled readers) should increase with an increase in syllable number, as each new syllable will require a new visual capture. The CDP++ makes a similar prediction, but this introduction will be limited to the MTMM as it makes specific predictions about developing readers. It proposes that because developing readers have had fewer encounters with words than skilled readers, they are more likely to use the analytical route for words, thereby activating syllable-level representations (Ans et al., 1998). Although the MTMM was modeled on French data, several developmental studies using different paradigms and languages support this prediction (French: Colé et al., 1999; English: Duncan & Seymour, 2003; Finnish: Hautala et al. 2012, Häikiö et al., 2015). Consequently, syllable information is part of a multi-layered structure of phonological information encoded during word recognition in skilled and developing readers (Ashby, 2010, Chateau & Jared, 2003). However, how and when these representations may change during reading development is poorly understood, particularly in English.

Two French studies indicate a difference in syllable processing between children and adults. Colé et al. (1999) assessed syllable processing using the syllable compatibility effect (faster detection of whether a target syllable, e.g., BA, was present in a target word BA.LLON compared to BAL.CON). Significant compatibility effects were only found for good readers (age 6), a year after reading instruction began. In contrast, adult readers showed syllable compatibility effects only for low-frequency words (Colé et al., 1999). Another French study revealed that syllable number predicted third graders' (age 8) reaction times in a naming and an online identification task (Bijeljac-Babic et al., 2004). However, fifth graders (age 10) showed no syllable number effects for both tasks. Adults, on the other hand, showed a smaller syllable number effect compared to the third graders only in the online identification task. Further evidence for the attenuation of syllable effects with an increase in reading skill has been documented in Finnish. Hautala et al. (2012) showed that lexical decisions and naming times of Finnish poor readers in grade two (age 8) increased as the number of syllables in the word stimuli increased, an effect that was absent for typical readers. In Spanish, it appears syllables are used similarly across second (age 7) and sixth (age 11) grades. In a word-spotting paradigm, readers were required to spot one-syllable words (*FIN*) embedded at the beginning of pseudowords which ended at a syllable boundary (*FIN-LO*) or not (*FI-NUS*; Alvarez et al., 2016). The results showed that these second and sixth graders were equally fast in the syllable boundary condition. Similarly, Hasenäcker and Schroeder (2016) reported that second (age 7) and fourth (age 9) grade German readers were unaffected by a syllable disruption manipulation where a colon was placed either at the syllable boundary or at a letter following the syllable boundary. However, both groups differed significantly from adults, who did not display reaction time differences based on where the colon was placed.

In English, two studies provide an indication that syllables are encoded. Juel and Holmes (1981) reported that second (age 7) and fifth (age 10) graders spent more time reading sentences with two-syllable words embedded compared to one-syllable words during both oral and silent reading. This syllable effect was greater in the oral reading condition. Interestingly, poor readers had a greater syllable effect than good readers during oral reading. However, the syllable effect was similar for both categories of readers in silent reading (see Figure 3 in Juel & Holmes, 1981). In another study, Duncan and Seymour (2003) found that 11-year olds made more errors on three-syllable non-words compared to two-syllable words non-words. However, no such effects were present for words. It is difficult to draw firm conclusions from these studies as syllable number was confounded by word length.

Regardless of the experimental manipulation, it appears syllables play an important role in children's word recognition. Sensitivity to syllable units is acquired soon after reading instruction begins for most languages (but see Campos et al., 2021 for diverging evidence in European Portuguese). This pattern may remain relatively stable during the primary years for Spanish and German readers (Alvarez et al., 2016, Hasenäcker & Schroeder, 2016). However, for English and

French readers, it may change depending on reading skill (Juel & Holmes, 1981) or grade (Bijeljac-Babic et al., 2004). Such cross-linguistic differences in the use of large grain size units such as syllables could be attributed to the degree of consistency of grapheme-to-phoneme correspondence between these languages proposed by the Psycholinguistic grain size theory (Ziegler & Goswami, 2005). Whilst German and Spanish have a shallow orthography, French has a deep orthography (Seymour et al., 2003). English language has an even deeper orthography (for spelling-sound correspondences) compared to all three languages (Borgwaldt et al., 2004). Therefore, developing English readers may be likely to use large grain sizes early on during reading instruction, such as syllables which are comprised of rime units that are mostly consistent in pronunciation across different words (Stanback, 1992) and rely less on syllabic representations as their reading skill and experience with print increases (Alvarez et al., 2016, Ziegler & Goswami, 2005).

Reading development and the eye-voice span

Sentence reading allows us to examine whether syllable effects generalize beyond word-level paradigms. This approach affords the opportunity of investigating children's reading development in its most natural and unobtrusive context. In addition, an oral reading paradigm allows us to measure the coordination of oculomotor, linguistic, and articulatory systems necessary for oral reading comprehension and fluency using the *eye-voice span* (EVS; Kim et al., 2019). The EVS is the distance between the eye and the voice during oral reading (Buswell, 1920, Inhoff et al., 2011, Laubrock & Kliegl, 2015).

According to Buswell (1920), a wide spatial EVS allows a reasonable unit of meaning to be recognized and integrated before articulation occurs. Therefore, the eyes travel ahead to allow processing of punctuation, context, and meaning, which ensures that reading occurs fluently. Without an EVS, reading would be monotonous, slow, and laden with errors, especially with homographs (words with same spelling but different pronunciation or meaning; Clark, 1995). This suggests that the EVS can be used as an index of reading fluency. For instance, non-fluent readers who are at the very beginning of reading instruction decode words by sounding out each letter and blending the sounds will have a significantly narrow EVS. However, as word familiarity increases, readers' lexical processing efficiency increases, and the span widens (Mancheva et al., 2015, Reichle et al., 2013). In line with this, Buswell's (1920) dated study showed that readers in grade two (age 7) already have an average EVS of 8-character spaces and college-age readers have an EVS of 15-character spaces. Similarly, Levin and Turner (1966) showed that second graders had a smaller EVS (2 words) compared to adults (4 words).

In summary, after a year of reading instruction, beginning readers show evidence of a span between the eye and the voice, and this span changes as reading experience accumulates. Additionally, the EVS represents a useful index to describe reading development. However, whether the change in the use of syllable units, as found in previous single-word naming studies, can be measured using the EVS remains an open question.

The present study

To ensure they had sufficient exposure to syllable instruction, children in years[1] three, four, and five were chosen to read aloud sentences embedded with six letter target words of either one or two-syllables controlled for number of phonemes. Our study is unique in permitting the use of several dependent measures to understand the time course of syllable processing across reading development. First, gaze duration is the measure of all first-pass fixations on a target word before moving away. This measure may be indicative of full lexical access (Reichle et al., 2013, Reichle et al., 1998). Second, articulation duration is the measure of the time between the start and end of target word articulation. This measure has been examined in relation to word length effects based on the possibility that children often begin articulation before decoding is complete (Gagl et al., 2015, Hautala et al., 2012). However, its use is far less common in studies examining syllable effects where the time between stimuli presentation and initiation of a vocal response (i.e., naming latency) is commonly used. Finally,

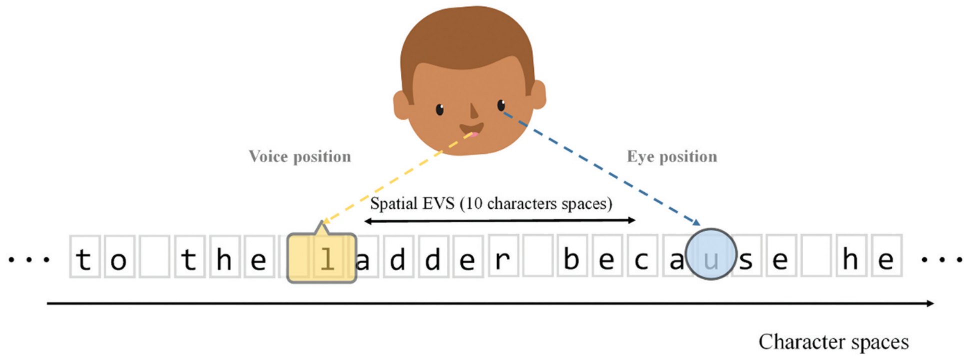

Figure 1. An illustration of the spatial EVS of the target word "ladder". Spatial EVS was measured as the number of character spaces between the first letter of the target word when its articulation begins and the eye-fixation position at that time

an important aspect of this study, is the examination of the spatial EVS, which measures how far the eyes are from the voice when the target word is about to be articulated (see Figure 1). We now turn to specific predictions regarding these measures for syllable number and year group.

Children process syllabic information after sufficient reading instruction (Bhattacharya & Ehri, 2004). The limited evidence on the syllable number effect in English developing readers (Duncan & Seymour, 2003, Juel & Holmes, 1981) prevents definite claims from being made. However, the existing evidence from skilled English readers (Jared & Seidenberg, 1990; Yap & Balota, 2009; but see Lee, 2001) and developing poor Finnish readers (Hautala et al., 2012) suggest that with more syllables, more time is spent during naming and lexical decisions. With null effects found in adults' eye movements during sentence reading (Ashby & Clifton, 2005, Drieghe et al., 2019), whether inhibitory effects are present for developing English readers is an important question. We propose that findings from naming tasks may extend to eye movement patterns (see Schilling et al., 1998). Additionally, children's eye movements show sensitivity to phonological information during silent reading (Blythe et al., 2015, Jared et al., 2016) and this may make it more likely that syllable effects are found especially during reading aloud (Juel & Holmes, 1981, Pelczarski et al., 2019). Hence, we predicted that gaze duration should be longer for two-syllable words compared to one-syllable words because words with more syllables have more vocalic nuclei which make them phonologically more complex in addition to stress assignment and vowel reduction processes (Perry et al., 2010, Yap & Balota, 2009).

It is possible that words with more syllables take longer to articulate due to intra-word pauses at syllable boundaries compared to words with fewer syllables (Proença, 2018). Hence, we predict that articulation duration will be longer for two-syllable words compared to one-syllable words. To our knowledge, word length effects (in letters) on the spatial EVS have been documented once by Halm et al. (2011). Halm et al. (2011) found longer words resulted in decreased spatial EVS. If the same length effects are applicable, we predict that EVS should be larger for one-syllable words compared to two-syllable words.

In line with previous eye movement studies (Hyona & Olson, 1995, Johnson et al., 2018, Rayner, 1986), we predict that gaze duration should decrease with higher year groups as access to the lexicon becomes faster. Greater reading experience as indexed by year may result in higher quality lexical representations which facilitate rapid and automatic word recognition processes (Perfetti, 2007, Perfetti & Hart, 2002). With age, spoken word duration decreases and oral reading rate increases (Hasbrouck & Tindal, 2006, Hulme et al., 1984). Therefore, we expect articulation duration to decrease with higher year groups. In agreement with prior studies (Buswell, 1920, Levin & Turner, 1966), we also expect the spatial EVS to increase with higher year groups. Based on the shift to global analysis of words (Ans et al., 1998) and use of larger grain sizes in English readers due to orthographic depth (Ziegler & Goswami, 2005), we predict a reduction in the syllable number effect for all measures as the year group increases.

Method

Participants

Sixty-four children (35 females) from two primary schools participated after parental consent and child assent were received. All participants reported normal or corrected-to-normal vision, no prior diagnosis of reading disorders and were fluent English speakers and readers. Seven participants spoke at least one other language apart from English. Results did not differ between excluding and including these participants, so they were kept in. Participants were naive as to the purpose of the experiment. One child did not complete the offline measures of reading and cognitive abilities due to school absence. The eye movement records of two children were discarded: one due to excessive head movements and the other due to at-chance comprehension score. Furthermore, due to technical errors, the voice recordings of 10 participants were lost. This left 51 participants with complete eye movement and voice recordings with an average age of 8.9 years ($SD = 0.9$ years; $range = 7–10$ years). Only the data from these participants were included in all descriptive and inferential statistics. This sample comprises 13 children in year three (6 females, $Mean = 7.8$, $SD = 0.5$), 21 in year four (13 females, $Mean = 8.8$, $SD = 0.5$), and 17 in year five (9 females, $Mean = 9.9$, $SD = 0.4$).

All children completed standardized measures of reading, spelling, naming speed, and intelligence (see Table 1 for summary). These were measured with the Test of Word Reading Efficiency 2-Form A (TOWRE-II; Torgesen et al., 1999), the spelling subtest of the Wechsler Individual Achievement Test II for Teachers (WIAT-II-T; Weschler, 2006), the letters and numbers subtest of the Rapid Automatized Naming and Rapid Alternating Stimulus tests (RAN/RAS; Wolf & Denckla, 2005), and the matrix reasoning and vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence II (WASI-II; Weschler, 2011). IQ scores were within the normal range of two standard deviations above and below the mean.

We explored differences in the offline ability measures between the three groups. Using standardized scores, one way analysis of variance showed that there was no significant difference in intelligence, $F(2,48) = 1.62$, $MSE = 244.8$, $p = .209$, rapid naming speed – numbers, $F(2,48) = .23$, $MSE = 121.8$, $p = .743$, letters, $F(2,48) = .21$, $MSE = 108.71$, $p = .815$ and spelling, $F(2,48) = 1.24$, $MSE = 153.2$, $p = .299$. However, there was a difference in total word reading efficiency, $F(2,48) = 7.10$, $MSE = 73.8$, $p = .002$, where year three children scored significantly better than year four children, $t(29.98) = 4.85$, $p < .001$, year four children were no different from year five children, $t(34.81) = -1.95$, $p = .059$, and year three children were not significantly different from year five children, $t(23.89) = -1.98$, $p = .059$. These analyses of total word reading efficiency indicated that children in year three were performing significantly better than the average (111) for their age compared to those in year four who were performing at the average level (100). Furthermore, derived sight word age equivalent scores indicated that year three and four children were performing at similar levels (see Table 1). The study was approved by Bournemouth University's Research Ethics Committee (ID 28325) and conforms with the Declaration of Helsinki.

Table 1. Mean and Standard Deviation (in parenthesis) of Children's standardized scores on off-line ability measures of participants by year group.

Measure	Year Three	Year Four	Year Five
WASI-II	105.8 (17.9)	106.7 (18.1)	114.7 (9.3)
Vocabulary	54.5 (12.9)	55.6 (10.3)	60.9 (7.0)
Matrix Reasoning	51.2 (7.8)	51.1 (10.5)	53.8 (6.1)
RAN/RAS-Numbers	110.6 (11.2)	108.1 (10.0)	107.7 (12.1)
RAN/RAS-Letters	103.7 (6.5)	101.5 (11.8)	103.0 (10.9)
WIAT-II-T-Spelling	105.2 (11.5)	101.4 (13.7)	107.7 (11.1)
TOWRE-II	111.9 (4.4)	100.6 (9.7)	106.7 (9.4)
TOWRE- Sight Word Efficiency	112.8 (6.1)	100.8(8.5)	103.1 (9.2)
TOWRE- Pseudo Word Decoding	110.0 (6.4)	100.4 (12.0)	109.8 (10.3)
TOWRE-II Sight Word Age Equivalent	9.2 (0.9)	9.2 (0.8)	11.0 (1.9)
Age (years)	7.8 (0.5)	8.8 (0.5)	9.9(0.4)

Note. WASI-II IQ scores are shown as standardized scores while mean T scores are shown for the Vocabulary and Matrix reasoning subtests.

Materials and design

There were 84 experimental passages which were comprised of two sentences spanning two lines, with each passage between 70 and 101 characters ($M = 87.2$ characters, $SD = 8.0$). The initial design was a two-year longitudinal study with 2 time points. As such, the 84 passages were split into two: each with 42 passages. Half the participants read one set, and the other half read the other set. This was so that each participant could see a different set of passages at another time point. However, after the initial data collection, the COVID-19 pandemic prevented data collection at timepoint two. Therefore, the experiment had two independent variables: syllable number (one vs two) as within-participant and year group (three, four, and five) as between-participant variables. A pair of one- and two-syllable target words with similar word frequency counts and number of phonemes (four or five) was embedded in the first sentence of either of two experimental passages (see Figure 2). Target words appeared 5.2 words on average into the sentence ($SD = 1.5$, $range = 3–10$)

All target words were six letters (see Supplemental file) and chosen from the Children's Printed Word Database (CPWD; Stuart et al., 2003). A group of 18 children ($range = 7–10$ years) independently rated how well target words fit into two sentence frames (A and B; see Figure 2) on a scale of 1 (very bad) and 4 (very good). See Table 2 for a summary of target word characteristics. Sixty-one target words (73%) had an age of acquisition (AoA) norm below 7 years, 20 had an average AoA of 8.5 years ($range = 7.1–11.5$), while 3 items did not have an AoA measure. Items were allocated to the different item sets based on sentence ratings and word frequency, such that each item set had similar sentence ratings. The mean word frequency did not differ between the two item sets F (1,80) = .03, $p = .86$ and two-syllable number conditions, $F(1,80) = .03$, $p = .88$, nor was there an interaction between item set and condition, $F(1,80) = .003$, $p = .96$. Furthermore, except for phonological neighborhood size, where there was a marginal difference between one- and two-syllable conditions, F (1,80) = 3.91, $p = .052$, and bigram frequency, where there was a marginal difference between item sets, F (1,80) = 3.77, $p = .056$; all other main or interaction effects of conditions and item sets for the target word characteristics were non-significant. The assignment of conditions to sentence frames and participants to item set was counterbalanced with a full-Latin square design across participants. Items appeared in a pseudo-random order for each participant.

Apparatus

Eye movements were recorded with an SR Research EyeLink 1000 Plus desktop-mounted eye-tracker with a sampling frequency of 1000 Hz. Although viewing was binocular, only the right eye was recorded (except for five participants who had the left eye recorded due to tracking

Condition	Sentence Frames
One syllable	A. He held tightly to the **branch** because he was scared. He had always been afraid of heights.
	B. The bird landed on the **branch** and rested there. Ed ran towards it and it flew away.
Two syllables	A. He held tightly to the **ladder** because he was scared. He had always been afraid of heights.
	B. The bird landed on the **ladder** and rested there. Ed ran towards it and it flew away.

Figure 2. Example of the experimental sentences.
Note. Target words were not formatted in bold in the experiment.

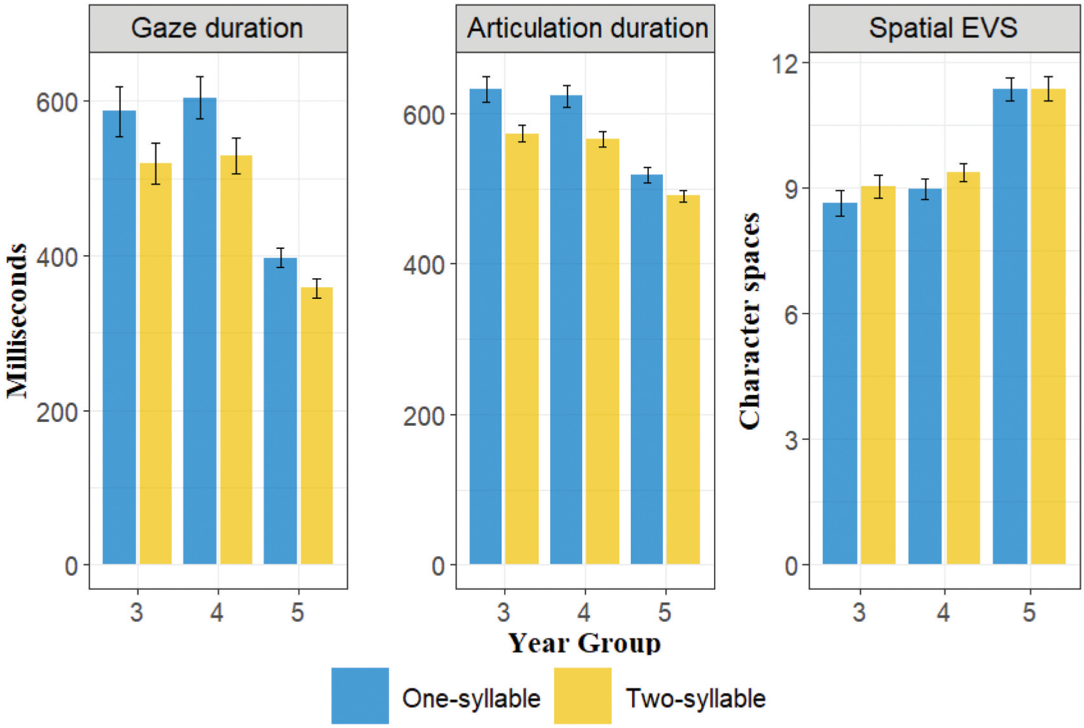

Figure 3. Bar plots showing means and ±1 SE for gaze duration, articulation duration and spatial EVS on target words by syllable number and year group.

Table 2. Mean target word characteristics as a function of number of syllables and item set (SD in parenthesis).

	Set 1		Set 2	
Measure	One-syllable	Two-syllable	One-syllable	Two-syllable
Phonemes	4.5 (0.5)	4.5 (0.5)	4.4 (0.5)	4.4 (0.5)
CPWD Frequency[a]	72.1 (93.2)	67.6 (82.2)	67.1 (114.8)	63.8 (101.2)
Target-word-in-sentence rating	1.6 (0.3)	1.6 (0.3)	1.6 (0.3)	1.6 (0.4)
AoA[b]	6.2 (1.5)	6.0 (1.8)	6.7 (1.7)	6.0 (2.0)
Orthographic N[c]	0.8 (0.8)	0.8 (0.8)	0.5 (0.7)	1.0 (1.1)
Phonological N[c]	3.1 (2.3)	2.0 (1.7)	3.1 (2.6)	2.2 (2.3)

Note. [a]CPWD frequencies given as occurrence per million words. [b] From Brysbaert and Biemiller (2017). [c]*N*= Neighbourhood, from the CPWD (Stuart et al., 2003).

problems). The stimuli were presented on a BenQ XL2410 T LCD monitor with a 1920 × 1080 screen resolution and 60 Hz refresh rate. Voice recordings were taken with a Fifine USB Microphone – K056 Model device with a lag range of 3 to 24 ms. Only the forehead rest was used to allow unhindered articulation while reading. The passage was formatted in a 22-point monospaced Consolas font and appeared as black letters over a white background. The passage was displayed over two lines. The lines were doubled spaced, justified to the left and presented in the middle of the screen vertically and with a 550-pixel offset horizontally. The eye-to-screen was 70 cm and each letter subtended ~0.34° horizontally.

The experiment was programmed in Matlab R2018a (MathWorks, 2018) using the Psychtoolbox v.3.0.11 (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen, Peters, & Palmer, 2002) libraries. The experiment was run on a Windows 7 operating system.

Procedure

The experiment began after participants gave written consent and verbal instructions were given. Participants were tested in quiet rooms within the school where they completed two sessions: an eye-tracking experiment and a paper-and-pencil offline assessment of reading and cognitive ability. Participants completed a 9-point calibration and validation procedure at the start of the experiment. Both procedures' accuracies were always <0.40 and recalibration was done whenever the drift check fell below this level and after a 2-min break scheduled in the middle of the experiment. Participants' fixation on a 50-pixel black gaze box centered at the first letter of the passage triggered the presentation of the passage. Participants were asked to read the passages aloud and to say "done" once they were finished so that the experimenter could terminate the trial. Participants answered TRUE/FALSE comprehension questions that appeared after 14 passages (33%) by pressing one of the two buttons on a keyboard. The experiment began with three practice trials to familiarize participants with the instructions. An example comprehension question for passages A in Figure 2 is "*He was not afraid of heights. TRUE/FALSE?"*. Both sessions of the experiment were run simultaneously by different experimenters and lasted for approximately 1 h. The order of the two testing sessions was based on each child's availability and the school timetable.

Data analysis

Eye movement data were manually pre-processed using Eye-doctor v.0.6.5 (Stracuzzi & Kinsey, 2009) to align fixations vertically with preceding and/or successive fixations on the same line. The EMreading R package (Vasilev, 2018) was used to extract fixation data for the analysis. Audio data were pre-processed manually using the PRAAT software (Boersma & Weenink, 2019). The waveforms, spectrogram, and formants were used jointly to determine the onset of articulation for each word in the text. Where co-articulation occurred, effort was made to allocate the boundary to a midpoint between the two words. An R script was developed to merge eye fixation data with audio text grids and compute the Spatial EVS.

Linear mixed models were used to analyze the data (lme4 package v1.1–21: Bates et al., 2015) in R software v 4.0.3 (R Core Team, 2020). Year group with three levels (three, four, and five) and syllable number with two levels (one-syllable and two-syllables) were treated as fixed effects. Successive difference contrasts were used to compare each year group with the next. Sum contrast was used to compare the syllable number condition coded as 1 to the grandmean (One: 1, Two: −1). Gaze and articulation durations were log-transformed due to skewed distributions (see supplemental file for untransformed analysis, which remains consistent with the results reported here) and spatial EVS was untransformed. Initial phoneme properties determine naming onset times, while initial and final phoneme properties determine the articulation duration (Hutzler et al., 2005). Consequently, whether the initial and final phonemes were voiced or voiceless was included into the articulation duration model as a covariate. Similarly, since the spatial EVS measure commences at the onset articulation, the initial phoneme voice characteristic was included in its model. These were done because the target words were not controlled for this feature experimentally. Additionally, because word frequency and age of acquisition varied within each condition, they were added as continuous covariates in all models. Due to a marginal difference between syllable number condition for phonological neighborhood size (see Materials), phonological neighborhood size was included in the models but was removed if it did not significantly improve the model fit using a likelihood test. All continuous covariates were centered to a mean of zero.

Participants and items were treated as crossed random effects. Initially, we adopted a full random structure (Barr et al., 2013), with random intercepts for participants and items, and a random slope for syllable number for participants. If this model did not converge, we removed random slopes. Only the gaze duration model excluded the random slope for syllable number. The results were considered as statistically significant if the $|t|$ values were ≥1.96. Cohen's d effect sizes are reported for the significant main effects.

Results

All participants scored above chance level (50%) on the comprehension questions (*M* = 84.9%; *SD* = 12.3%; *range* = 64.3–100%). Six trials were removed due to tracking loss. Fixations less than 80 ms within one-character of a temporally adjacent fixation were merged, while other fixations that were less than 80 ms were discarded (11.68%). Two data files were created, one for the gaze and articulation duration analysis and the other for the spatial EVS analysis. The following exclusions were made from both data sets: trials in which participants made errors on target words (5.09% and 4.71%), found target words difficult to pronounce (3.05% and 3.26%), read the trial silently before reading aloud and trials with long pauses and several errors in the trial (1.42% and 1.17%). Additionally, words with blinks (7.07%) were removed from the gaze and articulation duration analysis, leaving a total of 1686 data points. Likewise, due to blink artifacts on fixations, while target words were being articulated, 4.01% of target words were removed leaving a total of 1898 data points for the spatial EVS analysis. There was no significant difference in the number of errors made for each condition ($b = 0.05$, $SE = 0.18$, $z = 0.29$, $p = .77$) or set ($b = 0.35$, $SE = 0.21$, $z = 1.66$, $p = .10$)[2], neither was there an interaction ($b = 0.10$, $SE = 0.18$, $z = 0.56$, $p = .58$). Descriptive statistics for all dependent measures by year group and syllable number are shown in Table 3.

The linear mixed model (LMM) results for gaze duration, articulation duration, and spatial EVS are shown in Table 4 and illustrated in Figure 3. The gaze duration result revealed that there was a main effect of syllable number ($d = 0.15$). Interestingly, gaze duration was longer when processing one-syllable words compared to two-syllable words which was opposite to our prediction. Additionally, children in year four had longer gaze duration on target words than those in year five ($d = 0.51$). However, gaze durations of children in years three and four did not differ. Frequency and age of acquisition had significant effects on gaze duration of target words in the usual directions. Specifically, gaze duration decreased with greater frequency and increased with greater age of acquisition. The interaction between syllable number and year group was not significant[3].

Year five children had significantly lower articulation duration than those in year four ($d = 0.46$). The effect of syllable number and its interaction with year group was not significant. However, age of acquisition influenced articulation duration where early acquired words had a shorter duration compared to late acquired words. Additionally, initial phoneme voicing contributed to the variance in the model where words beginning with voiced phonemes were faster to articulate than words with voiceless initial phonemes.

Children in year five had a larger spatial EVS than children in year four ($d = -0.47$). However, children in year three and four did not differ significantly in the spatial EVS measure. The main effect of syllable number and its interaction with year group was not significant. Furthermore, as the age of acquisition of words increased, spatial EVS decreased significantly.

Bayes Factor and Power Analyses

To explore the observed null effects and assess the effect of the limited sample size, we conducted Bayes Factor analysis using the BayesFactor package (Rouder et al., 2012) and sensitivity power analysis using

Table 3. Mean and Standard Deviations (in parenthesis) for dependent measures across year group and number of syllables.

	Year Three		Year Four		Year Five	
Syllable	One	Two	One	Two	One	Two
Gaze duration (ms)	587 (458)	520 (390)	604 (509)	530 (440)	397 (215)	358 (218)
Articulation duration (ms)	632 (236)	573 (159)	623 (271)	566 (179)	518 (171)	490 (133)
Spatial EVS*	8.6 (4.5)	9.0 (4.0)	9.0 (4.8)	9.4 (4.1)	11.4 (4.7)	11.4 (4.9)
Spatial EVS in words	1.1(1.0)	1.3 (0.9)	1.2 (1.1)	1.3 (1.0)	1.7 (1.1)	1.7 (1.1)

Note. Spatial EVS was measured as number of character spaces between initial letter of the target word when it was articulated and the fixation location in the passage.

Table 4. LMM analyses showing gaze duration, articulation duration, and spatial EVS as a Function of year Group and number of syllables.

	b	SE	t	p
Gaze duration[a]				
Intercept	2.607	0.017	154.505	<0.01
Syllable number	**0.022**	**0.01**	**2.302**	**0.024**
Year Group 3–4	0.013	0.037	0.339	0.736
Year Group 4–5	**−0.147**	**0.035**	**−4.233**	**<0.01**
Word Frequency	**−0.03**	**0.01**	**−3.116**	**0.003**
AoA	**0.044**	**0.01**	**4.581**	**<0.01**
Syllable number * Year Group 3–4	0.006	0.015	0.388	0.698
Syllable number * Year Group 4–5	0.002	0.014	0.141	0.888
Articulation Duration[b]				
Intercept	2.734	0.016	175.258	<0.01
Syllable number	0.004	0.008	0.515	0.608
Year Group 3–4	0.002	0.022	0.11	0.913
Year Group 4–5	**−0.074**	**0.02**	**−3.663**	**0.001**
Word Frequency	−0.007	0.006	−1.037	0.303
AoA	**0.035**	**0.006**	**5.472**	**<0.01**
Phonological Neighbourhood size	*-0.011*	*0.006*	*-1.695*	0.094
Initial phoneme voicing	**0.022**	**0.007**	**3.076**	**0.003**
Final phoneme voicing	−0.006	0.016	−0.379	0.706
Syllable number * Year Group 3–4	0	0.008	−0.052	0.959
Syllable number * Year Group 4–5	−0.005	0.007	−0.762	0.45
Spatial EVS[c]				
Intercept	1.407	0.068	20.838	**<0.01**
Syllable number	0.035	0.054	0.64	0.524
Year Group 3–4	0.03	0.127	0.24	0.811
Year Group 4–5	**0.475**	**0.117**	**4.053**	**<0.01**
Word Frequency	−0.007	0.051	−0.146	0.885
AoA	**−0.223**	**0.05**	**−4.456**	**<0.01**
Phonological Neighbourhood size	0.006	0.049	0.126	0.9
Initial phoneme voicing	*-0.099*	*0.055*	*-1.804*	0.075
Set	*0.103*	*0.061*	*1.684*	0.095
Syllable number * Year Group 3–4	0.019	0.059	0.328	0.744
Syllable number * Year Group 4–5	0.038	0.054	0.691	0.493

Note. Statistically and marginally significant *t* values are formatted in bold and italics. Frequency and AoA were centered to a mean of 0. Phonological N did not improve the model fit for GD. Tables with random effects structure are included in supplemental file.

the *simr* package (Green et al., 2016). In the Bayes Factor analyses, we compared the full articulation duration and spatial EVS models to models that excluded the main effect of syllable number. These yielded Bayes Factor of 0.002 ± 13.73% and 0.002 ± 2.37% for the articulation duration and spatial EVS models, respectively. Similarly, comparing full models to models without the interaction between syllable number and year group yielded Bayes Factors of 0.097 ± 1.3%, 0.013 ± 4.2%, and 0.017 ± 1.8% for gaze duration, articulation duration, and spatial EVS models, respectively. With Bayes Factors of less than 1/3, these provide strong evidence for the null effect of syllable number on articulation duration and spatial EVS as well as the interaction effects of syllable number and year group on all three dependent measures.

Considering the crucial and significant main effect of the syllable number on gaze duration, we could detect only an effect of 43 ms with 80% probability. Power simulations revealed that 250 participants would be required in future studies to achieve 80% power with our observed effect size of 31 ms.

Discussion

The present study investigated changes in syllable use among year three, four, and five children using simultaneous eye movements and voice recordings. Contrary to our expectations, gaze duration was longer for one compared to two-syllable words suggesting that children spent less time processing two-syllable compared to one-syllable words. In line with our hypotheses, gaze duration and articulation duration decreased with higher year groups but only significantly so for the year four and five contrast. Similarly, year five children had a larger spatial EVS compared to year four children. Additionally, there was neither evidence of a syllable number effect on articulation duration and spatial EVS nor evidence of an interaction between syllable number and year group for any of the dependent measures.

The direction of the syllable number effect is in the opposite direction compared to most of the previous experimental and corpus analyses of syllable number effects. In English, taking longer to process, recognize, or name words with more syllables compared with fewer syllables is considered typical and an inhibitory effect (Stenneken et al., 2007, Yap & Balota, 2009). Furthermore, this pattern has been documented mostly in adults (Jared & Seidenberg, 1990; Pelczarski et al., 2019; Yap & Balota, 2009; but see Lee, 2001) and scarcely in children (Duncan & Seymour, 2003, Juel & Holmes, 1981). Precisely why our results diverge from this pattern is not immediately obvious. The argument that methodological differences could account for the discrepancy is countered by evidence from Pelczarski et al. (2019) who found an inhibitory effect of syllable number on eye movement measures in a study where participants named non-words as their eyes were tracked. This finding is comparable with behavioral experiments such as Jared and Seidenberg (1990) who found it took longer to name low-frequency words that were two-syllables compared to one-syllable. However, a similar pattern has also been found for not only low-frequency words but also high-frequency words in an analysis of data from the English Lexicon Project (New et al., 2006, Yap & Balota, 2009). Clearly, the opposite effect found in this study cannot be attributed to methodological differences (i.e., eye movement versus naming latency measures) or the absence of a word frequency manipulation as word frequency was controlled for. It is likely that stimuli and sample characteristics may interact to explain the observed differences between these studies and the current study (see below for further discussion).

In contrast to these inhibitory effects reported by Jared and Seidenberg (1990), Lee (2001) manipulated word length (four and six letters) and syllable number (one and two-syllables). For the six-letter condition, they found skilled adults took longer to name one-syllable words compared to two-syllable words, similar to what we found for gaze duration in the current study suggesting a facilitatory effect. However, an inhibitory effect was found for the four-letter condition. Lee (2001) attributed these findings to the spelling-sound mappings where each phoneme in two-syllable words mapped on to a single grapheme, whereas some phonemes in one-syllable words mapped on to multi-letter graphemes. Such multi-grapheme mapping was more common in the six-letter condition than the four-letter condition. However, this explanation cannot hold for the current study as the number of phonemes and graphemes were controlled for across the two conditions.

A more plausible explanation may be the occurrence of consonant clusters, which are more likely in one-syllable words (Frederiksen & Kroll, 1976, McLeod & Arciuli, 2009). Consonant clusters have been found to be slow processing (Bruck & Treiman, 1990, Frederiksen & Kroll, 1976, Treiman, 1985, 1991). Bruck and Treiman (1990) attributed children's difficulties with consonant clusters in phoneme recognition, phoneme deletion, and spelling tasks compared to single consonants to the perception of consonant clusters as whole units. Therefore, developing readers may find it difficult to segment individual phonemes in consonant clusters during reading aloud. In line with this, Gagl et al. (2015) showed that one-syllable German words with consonant clusters (*Herbst*) yielded longer naming latencies than two-syllable words with the same number of letters and phonemes but without clustering (*Mantel*) in developing readers. However, this facilitatory trend was driven primarily by six-letter words rather than four-letter words, where a trend of inhibition was apparent (Appendix C; Gagl et al., 2015). The presence of consonant clusters becomes more likely in one-syllable words than in two-syllable words as word length increases and is controlled. In the current study, 93% of one-syllable words and 2% of two-syllable words had consonant clusters at the onset. Why then did Jared and Seidenberg's (1990) experimental study find inhibitory effects for six letter words which had consonant clusters for the one-syllable compared to the two-syllable condition? The number of phonemes was not controlled, with most two-syllable words having more phonemes than one-syllable words. Alternatively, adult readers may produce a different pattern of results due to having less difficulty with consonant cluster compared to children (Treiman et al., 1982). While our experiment was not designed to investigate consonant clusters, we consider it a potential explanation. With respect to Ehri's model, this suggests that consolidation of larger units of recognition such as syllables may depend on the complexity of the syllable's internal structure, such as the presence or absence of consonant clustering. The implication of this for the MTMM is that consonant clustering may induce a processing cost for words with fewer syllables compared to words with more syllables of the same length.

An alternative explanation for a facilitatory effect could be that initial syllables may serve as crucial activating units during visual lexical access. The basic orthographic syllable of a word is thought to activate lexical representation of words (see Taft, 1986). Similarly, the first syllable frequency influences lexical access (Carreiras et al., 2005, Hutzler et al., 2005, Macizo & Van Petten, 2006). Therefore, if the first syllables are "access codes" used during multisyllabic word reading (Taft, 1986), then two-syllable words whose first syllable is likely four letters or less may have been activated more quickly than one-syllable words whose first syllable would always be the whole word (i.e., six letters in the current study). In addition, the recognition of the first syllable of a two-syllable word would potentially activate more lexical candidates; for example, *pur-* may activate *purple*, *purpose* etc., leading to facilitation in English (Macizo & Van Petten, 2006) and is consistent with our findings. Studies by Milledge et al. (2021) and Pagan et al. (2016) showing significant costs to substituting and transposing the first three letters of a two-syllable word in the parafovea may provide support that beginning letters are crucial for lexical access. However, the extent to which such syllable information can be processed parafoveally needs to be empirically tested in children (see Ashby & Rayner, 2004 for evidence of parafoveal processing of syllables in adults).

The reduction of gaze duration with year group results from an increase in lexical processing efficiency (Mancheva et al., 2015, Reichle et al., 2013). This finding agrees with previous eye movement research (Blythe & Joseph, 2011, Vorstius et al., 2014). Analysis of the sight word reading age equivalent scores across the three groups (see Table 1) revealed no difference between years three and four, but a significant difference between years four and five similar in the gaze duration measure. This corroborates the finding that reading proficiency rather than age-related changes explain changes in oculomotor control during reading (Blythe & Joseph, 2011). A similar year group effect was found for articulation duration, where this time was shorter for children in year five than year four but not significantly different between years three and four. Therefore, other stages beyond phonological encoding, word recognition, and semantic integration such as articulatory planning and production reflect lexical skills rather than just speech maturation that comes with age. While evidence points to an age-dependent decrease in speech and articulation rates (Hulme et al., 1984, Sturm & Seery, 2007) resulting from the maturation of speech motor organs (Kent, 1976), our findings support the view that cognitive skills in the form of reading expertise also shape articulatory processes. For example, Popescu and Noiray (2021) show that better readers show less intersegmental coarticulation (a measure of speech fluency) while repeating non-words. Additionally, children with reading difficulties make more speech production errors during picture naming and repetition of multisyllabic words and phrases (Catts, 1986). Such a proposal is consistent with the idea that the language domain influences speech production processes (German & Newman, 2007, Saletta et al., 2015).

For the first time in a little over a century, we document age effects (indexed by year group) on the spatial EVS using modern eye-tracking equipment. The results replicate previous research showing that the EVS increases with an increase in age (Buswell, 1920, Levin & Turner, 1966). More importantly, it indicates that reading proficiency may be more vital to predicting the EVS than age as no difference in the EVS was found for years three and four. At the onset of target word articulation, the eyes of year five children were two character spaces ahead compared to year four children. Further analysis using the EVS in words revealed that approximately one word intervened between the eye and the voice for year four children and two words for year five children (see Table 3). This suggests that the spatial

EVS reflects ease of word recognition, oral reading fluency and increased capacity to hold information in working memory for later articulation (Laubrock & Kliegl, 2015). Combined with historical evidence, our findings support Buswell's finding that between years three and five (US grades two and four), the average EVS is about 10 characters (see Table 1 & 2; Buswell, 1920). However, our findings are at odds with an EVS estimate of three words for grade two children measured using the lights-off paradigm (Levin & Turner, 1966) and suggest that this paradigm overestimates the EVS for a developmental sample (see Laubrock & Kliegl, 2015 for evidence in adults).

Other landmark effects in word recognition and reading research exerted strong influences on one or more of our dependent variables. Word frequency and AoA significantly predicted gaze duration replicating prior research (Dirix & Duyck, 2017, Joseph et al., 2013, Juhasz & Rayner, 2006). However, only AoA significantly predicted articulation duration and spatial EVS. It has been suggested that the early acquired words may serve as hubs within semantic networks (Steyvers & Tenenbaum, 2005), which provides them a benefit, above and beyond word frequency, in word recognition tasks. Therefore, if early AoA words hold a special place within semantic networks, they may also lead to benefits in semantic integration with other words of the sentence resulting in benefits beyond gaze duration. This may provide some basis for the differentiation of AoA effects above frequency effects for developing readers (Juhasz & Sheridan, 2020).

There were several null effects in this study. While most studies have found syllable number effects using the naming latency measure in adults (i.e., time to begin articulation; Jared & Seidenberg, 1990, Yap & Balota, 2009), we found no evidence of syllable number effects on articulation duration. This contradicts the idea of intra-word syllabic pausing in typically developing readers (Proença, 2018). Additionally, we failed to find evidence that syllable effects influence stages beyond word identification as spatial EVS did not differ significantly between our syllable conditions. This null effect is consistent with findings on delayed naming where syllable effects are absent (Juphard et al., 2006). In addition to these, there was no evidence that the use of syllable information, as indexed by syllable number, changes across years three, four, and five for any of the measures. English is considered a deep orthography with inconsistent spelling-to-sound mappings where the same spelling may yield different pronunciations and the same pronunciations may yield different spellings. Therefore, it may take time for readers to develop an understanding of these inconsistencies. If so, readers in higher year groups may respond to one- and two-syllable words as whole units compared to readers in lower year groups. The absence of an interaction between syllable number and year groups may indicate that the use of syllable units is relatively stable from years three to five, similar to what has been found in Spanish (Alvarez et al., 2016) and German (Hasenäcker & Schroeder, 2016). However, further exploratory analysis of the offline ability measures showed that sight word efficiency interacted significantly with the syllable number within our sample (see Table S7; Figure S1 in the Supplemental file). Previous evidence examining reading skill differences in the syllable number effect has yielded inconsistent results in adults. Butler and Hains (1979) reported an interaction between syllable number and vocabulary score on naming latency only when the main effect of syllable number was excluded from the model. Therefore, although Bayes Factor analyses provided strong evidence for null interaction effects between syllable number and year group, these findings should be interpreted with caution.

Limitations and future directions

The current findings and corresponding theoretical implications regarding the syllable number and its interaction with year group need to be considered as preliminary. The direction and size of the syllable number effect could be attributed to the consonant clustering confound in our target words and low power, respectively. While there was an attempt to control for as many variables experimentally, access to a limited range of words available in the CPWD and holding sentence frames constant across conditions (see Figure 2) meant that some variables would have proved difficult to control. With variability in the syllable number effect across studies, we make the following recommendations. First, future studies should control for consonant clustering and initial phonemes, which impact outcome measures especially during speech production tasks (Balota et al., 2004). Perhaps, this may be better achieved using non-words with a learning phase. Second, considering the possibility that the direction of the observed effects may have been due to the articulatory requirement, a silent reading baseline condition should be included. Third, because larger samples are required to detect interaction effects, we propose that after critical consideration has been given to design decisions, large samples should be used to assess these effects. Finally, to address any potential changes in children's sensitivity to sublexical units, an individual differences approach or investigating changes outside these three year groups, i.e., year two and six, and comparing to a group of skilled adult readers may further substantiate whether the observed effect changes with reading experience or skill.

Conclusion

This study was the first to examine syllable number effects in English developing readers using simultaneous eye movement and voice recording. Whether the observed facilitatory effects on gaze duration are true syllable number effects is open to further exploration. Nevertheless, these findings further our understanding of word recognition during oral sentence reading and suggest that children's eye movements may be sensitive to the complexity of sub-syllabic units (e.g., consonant clusters). Despite advancements in reading instructional methods over the last century and our use of more sophisticated eye-tracking equipment, the average EVS estimate obtained for our sample agrees closely with Buswell (1920). Such reliability over time justifies the call for more research to disentangle specific aspects of cognition and written language processes that the EVS reflects.

Notes

1. Year rather than grade is used as the data was collected in the UK. Children in year three would have received three years of formal literacy instruction including reception year.
2. A marginal difference between the two item sets were found, therefore this factor was included in the models if it improved the model fit.
3. The offline measures in Table 1 were examined in relation to the syllable effect. Only sight word efficiency subtest of the TOWRE led to a significant interaction (see Supplemental file).

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The datasets generated and analyzed during the current study are available in the Open Science Framework (OSF) repository, https://osf.io/p2q45/?view_only=d64833a08f614cd5ad2423597aa725c6.

Ethics approval statement

All procedures in this study involving human participants were approved by Bournemouth University's Ethics Committee (ID 28325) and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

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