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Orthography, and the Development of Reading Processes:
An Eye-Movement Study of Chinese and English

Gary Feng

Duke University

Kevin Miller

University of Michigan

Hua Shu

Houcan Zhang

Beijing Normal University

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Address correspondence to: Gary Feng, Department of Psychology: Social and Health Sciences, Box 90085, Duke University, Durham, NC 27708. (email: *garyfeng@duke.edu*).

Abstract

As children become proficient readers, the mechanics of the eye movements underlying reading undergo substantial changes. At least three factors might account for these changes: general developmental changes, effects of increasing reading expertise, and tuning of reading processes to take advantage of the regularities of the orthography children read. Cross-cultural developmental studies looking at the course of reading acquisition in different orthographies are crucial to disentangling these factors. Chinese characters and English alphabetic orthographies provide a good comparison for looking at how orthography affects the development of reading eye-movements. Third-grade, fifth-grade, and undergraduate students, native speakers of either English or Chinese were asked to read age-appropriate texts in their native language while their eye movements were recorded. Different aspects of reading eye-movements showed different patterns of influence by development and orthography. In general, orthographic effects were greater for children than those previously reported for skilled adult readers. The specific patterns of development in these two orthographies support a distinction between *when* and *where* systems of eye-movement control with different developmental trajectories. Consequences of these varying patterns for constraining models of reading and its development are discussed.

Orthography, and the Development of Reading Processes:
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As children become proficient readers, the mechanics of reading eye movements undergo substantial change. On average the duration of fixations (the period when the eyes stay relatively motionless) decreases, and the length of saccades (the jumps between fixations) increases. Between them, these changes lead to a more than tripling of reading speed between first and twelfth grade according to one estimate (Taylor, 1965). This is a remarkable developmental change, and understanding the sources of development in the mechanics of reading may provide a key to understanding the nature of reading and its development.

Three kinds of factors might account for these changes. The first involves maturational changes in general processing resources. A classic example is the processing speed models proposed by Kail (1986); across a variety of domains, there are remarkable and often parallel increases in the speed with which children perform cognitive tasks. The ability to inhibit inappropriate responses, which is linked to maturation of the brain, particularly the prefrontal cortex, has also been shown to play an important role in the planning of saccadic eye movements (Fischer, Biscaldi, & Gezeck, 1997; Klein & Foester, 2001; Luna et al., 2001; Luna et al., 2004). Age-related differences in reading eye movements may simply reflect improved efficiency through these and other maturational processes.

The second source of increasing reading facility involves general factors that are inherent in the process of reading, such as word recognition and sentence comprehension. These processes are experience-related rather than maturational, but they reflect aspects of reading that are so universal that experience in reading any orthography should lead to similar patterns of increasing eye-movement efficiency.

The third factor that might account for increasingly efficient eye-movement control with developing reading skill involves efficient adaptation and exploitation of the features of a particular orthography. To the extent that writing systems differ in their structure and fundamental units, one might expect that the developmental course of reading eye-movement control would differ among children learning to read such different orthographies. This would only be true to the extent that children's reading processes are sensitive to the factors represented by those orthographic differences, and so understanding the nature and timing of effects of orthography on reading will provide an insight into the developing flexibility of reading processes.

In an attempt to separate contributions of these three factors to reading development, the present study compares eye movements of children and adults who are speakers of two very different languages – English and Chinese. Because the orthographies used to write these two languages differ so greatly, comparisons of the developmental course of reading in Chinese and English provide a good basis for beginning to disentangle universal from script-dependent aspects of reading development. Before introducing the design of the study, we will first review existing data on developmental changes in reading eye movements among readers of English, then discuss features of the English and Chinese orthographies relevant to reading, and finally discuss existing eye movement data on reading in these two orthographies.

Developmental changes in reading eye movements.

Much of what we know about reading eye movements comes from studies of proficient readers or of those who have severe difficulties in reading (see Rayner, 1998). Studies on the normative development of reading eye movements are few and far between (see, Buswell, 1922; Judd, 1918; McConkie et al, 1991; Rayner, 1986; Taylor, 1965), but the overall developmental trajectory of reading eye movements is clear – eye movements become more efficient with reading proficiency. Specifically, average fixation duration declines with age, while mean saccade length increases. For example, McConkie et al. (1991) reported that in a longitudinal study the average fixation duration decreased from 304 msecs in first grade to 262 msecs in third grade and then to 243 msecs in fifth grade, and the mean saccade length increased from 3.6 letters to 5.7 and to 6.3 letters, respectively. A number of other eye movement variables also show consistent developmental changes. The number of fixations per 100 words, an index of children's reading efficiency, drops from first through sixth grade (Buswell, 1922; Taylor, 1965; Rayner, 1985, 1998). This measure is difficult to interpret because it combines different kinds of fixations, specifically those that move forward, regressions to previous sections of the text, and refixations on the same words. As will be shown in the present study, these different kinds of saccades show different developmental patterns. A different measure, within-word refixations, seems to be a particularly sensitive index of reading development. McConkie et al. (1991) reported that first grade children refixated five-letter words 57% of the time, versus 15% among fifth graders. Overall, the percentage of words receiving multiple fixations showed a substantial drop across the elementary school period. Meanwhile, the probability of word skipping, a positive index of reading expertise, increases during elementary school. Interestingly, while other aspects of eye movements go through significant changes, the proportion of regressive eye movements seems to remain flat throughout elementary years (see McConkie et al., 1991 for a review).

With the exception of regression rate, trajectories of eye movement development seem to converge on a simple developmental story, in which the eye movement control system continues to improve its efficiency throughout the elementary grades. The picture becomes more complex, however, once we go beyond these simple averages. For example, first grade students' landing position distribution (see McConkie et al., 1988) is nearly identical to that of skilled readers, suggesting that the oculomotor mechanism for saccade targeting in reading is already in place when children begin to read (McConkie et al., 1991). Similarly, the mechanism that controls fixation duration is also less susceptible to developmental forces than first appears. Although mean fixation duration declines with age, the modes (peaks) of fixation duration distributions remain nearly constant across age groups, all at around 180 msec (McConkie et al., 1991). Young readers have longer mean fixation duration primarily because they make higher proportions of long fixations, which are often associated with failures of cognitive control and inhibitory processes in oculomotor (see Findlay & Walker, 1999) and reading tasks (Yang & McConkie, 2001). Together, these findings suggest that the development of reading eye movement is not monolithic, with some aspects well developed by the time a child learns to read while others continue to improve.

The above picture is consistent with recent findings on oculomotor development in non-reading tasks. It is generally accepted that eye movements are controlled by two systems – the *when* system that is responsible to maintain a stable fixation, and the *where* system that determines where to move the eyes next and initiates saccadic movements (Findlay & Walker, 1999). Fischer et al (1997) provided experimental evidence distinguishing oculomotor processes responsible for maintaining fixations and those for voluntary control of saccades (initiating saccades and inhibiting inappropriate responses). Only the latter is correlated with age (within the range from 8-30 years). Thus it appears that the fixation system (the when system) is developed earlier, while the voluntary control of eye movements (the where system) depends on children's ability to inhibit reflexive responses, which is in turn linked to prefrontal cortex development that continues well into adolescence. Followup studies by Klein and Foerster (2001) further illustrated uneven development rates for aspects of eye movement control typically attributed to prefrontal functioning.

In summary, although what we know about reading eye movement development is sketchy, there is converging evidence that aspects of the oculomotor system may be differentially influenced by maturational and/or experiential factors. Specifically, the mechanism for fixation control (the when system) appears to be fairly well developed by the beginning of elementary school, as does the involuntary programming of saccades (c.f., McConkie et al., 1991). On the other hand, eye movement control that involves voluntary or cognitive control may continue to develop (Fischer et al., 1997; Klein & Foerster, 2001; Luna et al., 2001; 2004). Comparisons of developmental trajectories among children learning to read different orthographies can play a key role in distinguishing these two kinds of processes.

Chinese and English orthographies: features relevant to reading

Chinese characters and the alphabetic orthography used to write English differ in a number of features with the potential to affect reading acquisition. The main features relevant here are: 1) the fundamental linguistic unit represented by the orthography, 2) the relative transparency of the orthography, and 3) the orthographic marking of boundaries between units. These features interact to produce important differences in the perceptible information available to readers of these two orthographies.

Fundamental orthographic units. English words are composed of a series of letters, which very roughly correspond to phonemes. This is not to say that English letters correspond to phonemes in any straightforward way (e.g., the letter pair "th" stands for one phoneme, but for different sounds in the words "them" and "theme"). Furthermore, beginning English readers tend to act as though letters represent phonemes more reliably than they do (Treiman, Weatherston, & Berch, 1994), and children's (and adult's) representations of the sounds of words are highly influenced by how those words are spelled (Ehri, Wilce, & Taylor, 1987), so that they are very likely to report that "pitch" has one more phoneme than does "rich."

With very rare exceptions, Chinese characters represent morphemes, and correspond to syllables in the spoken language. Characters cannot be further decomposed into smaller phonological units. Thus, the Chinese and English orthographies differ in the size of the smallest phonological unit represented, the syllable in the case of Chinese and the phoneme in the case of English. This in turn has consequences for the phonological transparency of the two writing systems, that is, the likelihood that a reader can pronounce an unfamiliar word.

Transparency of writing systems. About 90% of Chinese characters are semantic-phonetic compounds (Hoosain, 1991), consisting of one part that has some relation to the pronunciation of the character and one part that has some relation to its meaning. What those parts are, what their relationship is with the meaning and pronunciation of the character, and whether a child would be able to take advantage of this relationship can be quite complex, however. The proportion of characters that are semantic-phonetic radicals varies greatly with frequency. Shu, X. Chen, Anderson, Wu, and Yue (2003) analyzed the 2,570 characters that Chinese children in the mainland are expected to learn by the end of grade 6. The percentage of characters that are semantic-phonetic radicals rose from 45% of characters introduced in grade 1 to a peak of 86% of characters introduced in grade 5, before dropping off slightly to 81% of characters introduced in grade 6. Characters that had the same pronunciation as their phonetic components or differed only by tone rose from 32% in grade 1 to a peak of 43% of the characters introduced in grade 6. An additional 25-30% of characters shared either onset or rime with their phonetic components. Thus, the morphology of Chinese characters provides useful clues to their pronunciation, but not in a way that children can expect to be able to "sound out" a new character. This is particularly the case for young children, who are more likely to be learning characters whose pronunciation cannot be derived from a phonetic component; even if it does, young readers may not know the character that serves as a phonetic component in a new character.

As is the case with Chinese, English contains many exception words whose pronunciation can not be inferred from their written representations. Good readers often have vocabularies that contain mispronounced words such as "epitome" or "melancholy" that entered their vocabulary from print (Nagy, Anderson, & Herman, 1987). But even in these cases most of the ambiguity is limited to stress and certain vowels. In general, a skilled reader has a good chance of guessing most, if not all, sounds of an unfamiliar English word (Venezky, 1999). The greater likelihood of being able to figure out new words for English may have consequences for eye movement control. For example, reader of English may be more likely to gain new information by repeatedly inspecting (refixating) a word than would a reader of Chinese.

<u>Orthographic marking of word boundaries</u>. A major difference between the two orthographic systems is that English texts consist of a series of words separated by spaces, while Chinese text consists of a series of evenly-spaced characters. Chinese words consist of one or more characters (with an average of 1.5 characters; Sun, Morita, & Stark, 1985), each of which typically corresponds to a morpheme, but there is no orthographic marking of word boundaries.

The difference in word spacing may have both conceptual and perceptual consequences. Perhaps in part because of the lack of conventions for delimiting words in writing Chinese, there is little consensus among Chinese speakers about what words are (Miller, S. Chen, & Zhang, 2004; Wang, 2003). If words have to be parsed at some point in the comprehension process, one would predict some processing costs associated with assembling characters into words in reading Chinese; these costs may be larger for beginning readers. The lack of word spacing may also lead to costs in visual perception and oculomotor planning. Skilled readers of English acquire word-length information parafoveally and use it in deciding where to look next (Morris, Rayner, & Pollatsek, 1990; Rayner, Sereno, & Raney, 1996); thus, short words are relatively likely to be skipped. The lack of orthographic marking of word boundaries in Chinese would preclude oculomotor strategies used by skilled readers of English that rely on word-length information obtained in preview (Pollatsek & Rayner, 1982; Rayner & Pollatsek, 1996), and could potentially interfere with efficient reading in Chinese.

Interestingly, the opposite prediction may also be made. Past research on Chinese reading has shown that adding spaces to separate words resulted in either no effect (Everson, 1986) or negative effects on comprehension (e.g., Liu, Yeh, Wang, and Chang, 1974). Thus it may be that skilled readers of Chinese can organize characters (morphemes) into words on the fly, without taking resources away from reading comprehension. Furthermore, there may be a trade-off between marking word boundaries (as in English) versus morpheme boundaries (as in Chinese). Although word spacing may make saccade programming a relatively straightforward task in English reading, it may impose costs as well as benefits because morphological boundaries are not marked. Long words are more likely to be refixated, and this may reflect some kind of morphological processing in which words are broken into smaller units. German is a language notorious for its long words (Twain, 1997/1880), of which a moderately long example is "Fussballweltmeisterschaftsqualifikationsspiel" (Soccer World Cup qualifying game). Inhoff, Radach, & Heller (2000) presented native German speakers with words and texts containing long compound words presented either normally (as above) or with spaces introduced to separate component words. For naming and in most reading tasks, performance improved when the long terms were parsed into smaller, meaningful units. The only exception was an increase in the final fixation on the compound word, which the authors interpreted as implying the need to resolve uncertainty about how the components were to be joined into larger compounds. These studies all involve skilled readers; whether and when sensitivity to the unit marked by an orthographic system develops will be explored in the current study.

Reading in Chinese and English: Eye movement patterns.

Given the large differences between the writing systems, one might predict distinct patterns of eye movements in reading Chinese and English. Research in the last 80 years, however, suggests that there are more similarities than differences among skilled readers of these two orthographies (e.g., Gray, 1956; Feng, Miller, Shu, & Zhang, 2001; Miles & Shen, 1925; Peng, Orchard, & Stern, 1983; Sun, Morita, & Stark, 1985; Tsai & McConkie, 1995; Tsai & McConkie, 2003; Yang, 1994; Yang & McConkie, 1994, 1999; see Feng, in press, for a review). For example, when native Chinese or English speakers read comparable scientific articles (Sun & Feng, 1999), critical eye movement variables, such as mean fixation durations (257 msec versus 265 msec), average saccade length (1.71 versus 1.75 words per fixation), and reading rate (386 versus 382 words per minute), were remarkably similar. Studies looking at perceptual span, the size of effective vision during a fixation, also show similarities in skilled reading of Chinese and English. For adult readers of English, the typical perceptual span for detecting spaces in the peripheral vision is approximately 3 letters to the left and up to 15 letters to the right of the gaze (McConkie & Rayner, 1975), and the span for letter identify is narrower, only up to 9 letter spaces, or approximately 1.5 words, to the right (Underwood & McConkie, 1985). The perceptual span in reading Chinese is estimated at approximately one character to the left and two to three characters to the right of the gaze position (Inhoff & Liu, 1998; Tsai & McConkie, 1995; Tsai, Tzeng, Hung, & Yen, 2000).

Assuming the average length of Chinese words is 1.5 characters (Sun, et al., 1985), the perceptual spans in reading Chinese and English are fairly close in word unit. Overall, global eye movement measures appear to be comparable between the two languages.

There are fewer than a handful of studies on reading eye movements of Chinese children. H.-C. Chen et al. (2003) reported a data set involving second-, forth- and sixth-grade students from Hong Kong reading sixth-grade level prose passages. Mean first fixation duration was 280, 253, and 232 msec., respectively, for the three grades. Average forward saccade length increased from 2.3 character spaces for the second graders to 2.6 for the older grades. The probability of regression remained virtually flat at around 15-17%. A decrease in the rate of within-word refixation was hinted by the large decline in gaze duration. Overall, the developmental pattern reported in H.-C. Chen et al. (2003) is consistent with the literature on English reading development summarized before.

Although research looking at college students' reading of Chinese and English has been notable for the cross-language consistency found in the mechanics of reading, this need not imply that the same patterns will be found for children. With less reading experience and more fragile skills, young children may be more affected by the characteristics of orthography than are adults. To our knowledge, the study reported here is the first cross-language developmental study that compares eye movements of Chinese- and English-speakers.

Predictions

Studies of the development of reading processes in children learning to read Chinese and English provide a powerful basis for disentangling the role of universal and script-dependent processes in the development of reading skill. Logically, there are three possible patterns of development among the different components of reading eye-movements:

Parallel development across writing systems. To the extent that some aspects of eye-movement control show parallel development across two very different writing systems, developmental explanations that refer to global cognitive change or universal aspects of the reading process are implicated. This is a plausible hypothesis for at least two reasons. First, maturational processes have been shown to play important roles in oculomotor development (Fischer et al., 1997). Second, existing studies suggest that reading Chinese is remarkably similar to reading English among skilled readers of the two orthographies (e.g., Gray, 1956; Sun & Feng, 1999). Whether the same pattern holds across development is an open question addressed in this research.

Script-dependent developmental patterns. As described above, Chinese characters and English alphabetic writing differ profoundly in their visual organization and in the way in which they represent their respective spoken languages. These differences may impose different demands on the oculomotor system and result in fundamentally different reading processes. Specifically, because (a) information is more densely packed in Chinese characters compared to English words (Hoosain, 1991), (b) characters provide less systematic phonological information, and (c) Chinese words are not separated by spaces, one might predict that Chinese children should tend to make shorter saccades and longer fixations on average, compared to their American peers. Together, these should lead to slower reading speeds among Chinese children.

But one might also make the opposite prediction. Chinese-speaking children may have developed script-specific oculomotor strategies early on, and thus not be negatively affected by the lack of word spacing. In addition, they may benefit from not having to break long words into smaller meaning units. If breaking up is indeed hard to do, then it should be readers of English who show disruption due to the need to parse long perceptual units in the course of reading. This disruption should show up in relatively more refixations of words among readers of English compared to their Chinese peers.

Interaction among maturation, experience, and orthography. The development of reading eye movements may be driven by a combination of maturational, experiential, and cultural (including orthographic) factors, and prior research suggests that different aspects of eye movement control may be differentially influenced by different combinations of these factors. As a result, instead of a monolithic developmental pattern, different parts of the eye movement control system may follow distinct developmental trajectories.

As already discussed, past research provides support for the idea that different aspects of the eye-movement control system show different patterns of development; with the system responsible for fixation duration (the when system) maturing relatively early (Fischer et al., 1997).

Comparisons of reading development in Chinese and English provide a strong test of the differentiation between these two eye-movement control systems, and lead to the following predictions: 1) Fixation duration should show similar developmental trajectories across age (McConkie et al., 1991) and languages (Sun & Feng, 1999). More specifically, the developmental changes in mean fixation duration should be due to a decrease of percentage of long fixations with age, as suggested by McConkie et al. (1991). 2) Saccade-related measures should show larger effects of orthographic variation.

Saccade programming (the where system) has been shown to be more affected by cognitive inhibitory control (Fischer et al., 1997) and shows larger developmental changes in non-reading tasks. This suggests that saccade control may be more susceptible to cognitive control (such as different reading strategies) as well as to influences of idiosyncratic features of writing systems. We therefore predict that saccade-related measures will demonstrate (a) substantial developmental changes and (b) clear cross-language differences.

Comparing the development of the mechanics of reading ordinary text for comprehension among children learning very different orthographies provides a powerful method of disentangling the skein of processes that combine to make fluent reading possible.

Method

Participants

The American participants were 23 third grader students (mean age 9.1 years, range 8.6 - 10.2; 12 males and 11 females), 30 fifth grader students (mean age 11.2 years, range 10.6 - 12.1; 15 males and 15 females), and 26 undergraduate students (14 males and 12 females) from two small towns in East Central, Illinois. As a group, children from the two Illinois schools tested above the 80th percentile in the Illinois State reading assessments. The Chinese participants were 25 third grade students (mean age 9.4 years, range 9.0 - 10.6; 12 males, 13 females), 25 fifth grade students (mean age 11.4, range 10.7 - 11.9; 12 males, 13 females), and 30 undergraduate students (14 males and 16 females) from Beijing, China. The Chinese school is located near downtown Beijing. At the time of the study it was well equipped but was rated as average in academic performance in its district. All participants in both countries had either normal vision or corrected to normal vision.

Materials:

Reading materials are described in more detail in Appendix A. In each language, we found seven age-appropriate short stories for third and fifth grade students. We did this by first obtaining a selection of stories from popular third- and fifth-grade extracurricular reading series in each country. We selected two stories from the third grade series and two from the fifth grade series for each country that were roughly matched in terms of their contents (e.g. biography, science, etc.) and approximate length. Teachers of the participating classes read the passages and judged them to be appropriate for their students. These passages provide a sampling of the kinds of reading that children in each country might be naturally exposed to, but none of our participants had read the stories prior to the experiment. We generated two comprehension questions for each story.

In addition to these stories, we also selected two passages - “The power of boats” (BOAT) and “The foolish mule” (MULE) - that had parallel English and Chinese versions and were within the reading abilities of both third and fifth grade participants. They were read by every participant and thus served as anchors for cross-cultural and cross-age comparisons. The two stories and the comprehension questions were originally used in a cross-cultural study of American, Japanese, and Chinese students’ reading abilities (Stevenson, Lee, C. Chen, & Stigler, 1990). Cultural biases and difficulty levels of these stories were controlled in the development of these materials. They were rated as having fourth grade and fifth grade difficulty levels in Stevenson et al.’s study, but our pretests and teacher interviews showed that most third graders had no difficulty with them.

As a check on the difficulty of the stories, we asked teachers in both countries to circle words (English) or characters (Chinese), that they thought would be difficult for an "average" student in their classes. On average, the Chinese materials contained slightly more unfamiliar characters (25 for third grade and 6 for fifth grade) compared with unfamiliar words in the English materials (17 for third grade and 7 for fifth grade).

Equating for length was complicated by the fact that Chinese orthography does not mark word boundaries, and educated Chinese-speaking adults do not necessarily agree on how to divide a passage into words (Hoosain, 1991; Miller, S. Chen, & Zhang, 2004; Wang, 2003). We identified words based on a word-segmentation standard developed for information-processing known as the Chinese National Standard GB13715 (Liu, Tan, & Shen, 1993). Statistics and analyses involving word-units in Chinese are all based on this standard.

Apparatus and Procedure

Participants were asked to read the stories silently as they ordinarily would and were told they would be asked some questions about each story after they were done reading it. Readers' eye-movements were recorded with an EyeLink I eye-tracking system, which is a head-mounted infrared system with 250 Hz sampling rate and a maximum spatial resolution of 0.005°, although the typical accuracy level is approximately 0.5 visual degree, measured by repeated calibrations.

Reading materials were presented on a computer screen 60-70 cm away from the reader. Children read the stories selected for their age group; adults read all of the stories.

The Chinese materials were displayed in 24 point Song font, corresponding to about 28 pixels or 1.3 visual degrees per character. An English letter was on average 7.3 pixels or 0.35 visual degrees. Each screen held a maximum of 7 lines of English text or 6 lines of Chinese text.

A 9-point calibration was done before each experiment and was repeated as necessary during the experiment. Drift-corrections were done between pages. Comprehension questions were presented after each story and were answered orally. The stories were presented in a fixed order in each language. Reading typically took approximately 10 to 20 minutes and participants could ask for a break at any time, which several children but no adults did.

Results

Reading comprehension

The rates of correct answers to the comprehension questions were on average 67.8%, 89.2%, and 97.2% for American third-graders, fifth-graders, and undergraduate students, respectively, and were 78.0%, 81.8%, and 94.4% for Chinese third-graders, fifth-graders, and undergraduate students, respectively. Because the reading passages and comprehension questions were different in the two languages, these numbers cannot be compared directly. Comparing comprehension levels for the “Boat” and the “Foolish Mule” stories is more straightforward, because the stories and questions are comparable across languages. The mean score for the four questions on these two stories showed no significant country difference between Chinese and American readers, $\underline{F}(1, 163) = 3.304$, $\underline{p}=.071$, but a significant developmental trend, $\underline{F}(2, 163) = 11.619$, $\underline{p}<.001$, (69.3%, 83.1%, and 90.4%, for American third-, fifth-graders and adults; 78.0%, 88.0%, and 97.7% for Chinese third-, fifth-graders and adults, respectively).

Reading speed

One prediction based on differences between the English and Chinese writing systems is that there may be more processing costs associated with reading Chinese, particularly for Chinese children. If this is true, one would expect slower reading and longer processing time per word. Figure 1 shows the average reading time per word, averaged across all stories; a separate analysis with only the BOAT and the MULE stories showed the same pattern. Reading time per word decreased with age, F (2, 148) = 83.46.14, $p < .001$, but there was a significant interaction between age and language, F (2, 148) = 3.36, $p = .037$. Paired comparisons within each age group showed that Chinese children read significantly or marginally significantly faster than their American counterparts, F (1, 148) = 4.95, $p = .028$ in third-grade, F (1, 148) = 3.85, $p = .051$ in fifth-grade, but the reading time for American and Chinese undergraduate students did not differ significantly, F (1, 148) <1. American readers' reading speeds, when converted into Words Per Minute (wpm), were approximately 110, 140, and 340 wpm for 3rd-grade, 5th-grade and undergraduate students, which is consistent with figures reported in prior literature (Carver, 1990; Rayner, 1998).

As we expected, although English and Chinese speaking adults read at a similar speed, large language differences were found among beginning readers. The direction of the differences, however, is opposite to the prediction laid out above, with an advantage for young Chinese readers despite the lack of explicitly marked word boundaries in their orthography. In the following analyses we decompose story reading time stories into two factors – number of fixations per word and mean fixation duration – and explore their relation to on reading speed.

Number of fixations

As shown in Figure 2, the number of fixations per word decreased with age, F (2, 148) = 94.30, p < .001, and was lower for Chinese than for English readers, F (1, 148) = 6.61, p =.011. There was again a significant interaction between age and language, F (2, 148) = 3.68, p = .028. The differences were significant at third-grade, F (1, 148) = 6.52, p = .012, and at fifth-grade, F (1, 148) = 6.02, p = .015, but non-significant for adult English and Chinese readers, F(1, 148)<1. The same pattern was found when the BOAT and MULE stories were analyzed separately.

Fixation duration

Mean fixation duration was approximately 263, 244, and 191 msec for American third grade, fifth grade, and adult readers, and 265, 238, and 212 msec for Chinese third grade, fifth grade students, and adults, respectively. Figure 3 shows the average duration of fixations of each group of participants for all valid trials. Mean fixation duration decreased significantly with age, F (2, 148) = 41.27, p < .001. There was no significant language main effect, F (1, 148) <1, nor any interaction between age and language, F (2, 148) = 2.06, p = .131. Average fixation duration did not differ significantly between American and Chinese children, F's (1, 148) <1 for both 3rd- and 5th-grade, whereas American college students' fixation duration was about 21msec faster than that of Chinese college students, F (1, 148) = 4.89, p = .029.

Cross-language similarities in fixation duration are further illustrated in Figure 4, which compares the frequency distributions of fixation duration for different reader groups. Only forward fixations were plotted, as regressive fixations are thought to have different functions than acquiring new information (Rayner, 1998). Two features are noteworthy on Figure 4. First, the distribution functions for both adult groups are quite similar. In particular, the peaks the distributions are identical. The slightly longer mean fixation duration among Chinese-speaking undergraduate students was because they made somewhat higher proportion of long fixations. Second, there is little change in the modes of distributions, both developmentally and cross-linguistically. This suggests that the developmental differences seen in Figure 3 are not caused simply by a leftward shift of the fixation duration distribution. Rather, developmental differences in the means are results of the slightly higher proportions of long fixations in children (and correspondingly lower percentages of short fixations).

Distributions of saccade length

Cross-linguistic comparisons of saccade length are complicated by the fact that there is not a common metric for English and Chinese texts. Because reading saccades are primarily affected by linguistic units (number of letters or words) rather than by font size and viewing distance (Rayner, 1998), saccade length is typically reported in letter spaces for English reading but in character spaces for Chinese reading. Arbitrary scaling factors have been proposed, such as two English letters for a Chinese character (Yang & McConkie, 1994), but their appropriateness is questionable (e.g., Hoosain, 1991; Feng, in press). In the present study we adjusted the font size in both languages so that a parallel story in English and Chinese (i.e. the Mule story) would have approximately the same number of lines in both languages. As a result, a Chinese character equals 3.9 English letter spaces. A typical six-letter English word therefore took approximately the same space as the average length of a Chinese word, which is 1.5 characters (Hoosain, 1991; Tsai, Lee, Hung, & Tzeng, 2001). This was obviously a crude attempt to equate the materials and was never intended to be a precise matching. Nevertheless, it allowed a comparison of saccade length in term of the screen pixels. Although any cross-language comparison of saccade-length will be problematic, developmental changes within country do not have these concerns.

On average, American readers' forward saccades were significantly shorter than those of Chinese readers. The length of forward saccades increased with age, $\underline{F}$ (2, 148) = 81.82, $\underline{p} < .001$, and was longer for Chinese than for English readers, $\underline{F}$ (1, 148) = 53.24, $\underline{p} < .001$, and there was no interaction between age and language, $\underline{F}$ (2, 148) < 1. There were significant country differences for each age group: $\underline{F}$ (1, 148) = 13.41, $\underline{p} < .001$ at third-grade, $\underline{F}$ (1, 148) = 24.53, $\underline{p} <.001$ at fifth-grade, and $\underline{F}$ (1, 148) = 16.64, $\underline{p} < .001$ for adults. Mean saccade lengths for American readers were approximately 5.5, 6.7, and 10.3 letter spaces for third grade, fifth grade, and adult readers, respectively. Saccade length averaged 2, 2.4, and 3.1 characters for Chinese third grade, fifth grade, and undergraduate students, respectively.

Frequency distributions of forward saccade length (in pixels) for American and Chinese children and adults are shown in Figure 5. While the peaks of English and Chinese adult readers coincide, possibly due to our effort to equate the physical length, American children made more short saccades and fewer long saccades than their Chinese peers. Because typical five-letter English word is approximately 37 pixels long, many of the short saccades made by American children would land on the same words. American undergraduate students, while still making fewer long saccades, were no more likely to make these short saccades than the Chinese counterparts.

Kinds of saccades: forward, refixations, and regressions

The large number of short saccades in American children's saccade distributions suggests that they made more within word refixations. To test this hypothesis, we divided fixations into three categories – progressive fixations, regressions, and refixations – based on whether they landed on a new word, a word that had been read, or the current word, respectively. Note that Chinese data were also analyzed by words, as defined in the GB13715 National Standard, rather than characters in this analysis.

The percentages of each category within each group are shown in Figures 6A-C. As is apparent from the figures, different patterns of country and developmental effects were found for the different kinds of saccades. Progressive fixations, increased significantly with age, F (2, 148) = 166.79, $p < .001$, and were higher for Chinese than for English readers, F (1, 148) = 10.70, $p = .001$, and there was a significant interaction between age and language, F (2, 148) = 6.49, $p =.002$. The proportions of forward saccades did not differ in adult readers, F (1, 148) = 1.06, $p =.305$, but differed significantly across languages at third-grade, F (1, 148) = 11.16, $p = .001$, and fifth-grade, F (1, 148) = 9.88, $p = .002$. Thus the difference in reading speed reflects the greater proportion of saccades among young Chinese readers that moved forward in the text.

A different pattern was found for regressions. There was a significant country effect $F(1,148) = 17.67$, $p < .001$, but not significant age difference nor a significant interaction. At all ages, Chinese readers showed more regressions than did American participants, F (1, 148) = 6.126, $p =.014$ for third-grade, F (1, 148) = 4.12, $p =.044$ for fifth grade, and F (1, 148) = 7.79, p = .006 for adults. The lack of developmental changes in regression rate may be surprising, given that the probability of making regressions is sensitive to syntactic difficulty, contextual support, and other text properties, all of which should no doubt vary in the reading materials used for different grades and in different studies. We do not have a ready explanation for the lack of developmental change. However, we are not alone in finding this pattern. Data summarized in McConkie et al (1991) showed that regression rate remains flat throughout elementary grades; H-C. Chen et al. (2003) also found that the regression rate remained at about 15% among Chinese readers ranging from second grade to college students. Future studies are needed to explore this phenomenon.

Refixations decreased with age, F (2, 148) = 161.81, p < .001.There was also a significant language effect, F (1,148) = 41.97, p < .001, and a significant age by language interaction, F (2,148)= 5.67, p=.004. American children, but not American undergraduate students, made significantly more refixations, F (1, 148) = 27.14, p < .001 for third grade, F (1, 148) = 21.82, p < .001 for fifth grade, and F (1, 148) = 1.31, p =.253 for adults.

There are at least two plausible explanations for the greater incidence of refixations among young readers of English compared with children learning to read Chinese. The first involves the possibility of sounding-out words in English versus Chinese and the second the problem of parsing English words into smaller morphologically meaningful units. A strategy of refixating unfamiliar words as part of an explicit “sounding out” strategy is certain to be more fruitful in English than in Chinese. On the other hand, we found the same pattern of more within word refixations among readers of English in our college student sample, who are most unlikely to need to sound out words in the children's texts used in this study.

Because Chinese and English differ in the size of the fundamental unit of writing, the differences in within word refixations may reflect problems in parsing words into morphologically meaningful units. Supporting this explanation are the results of Inhoff et al. (2000), who found that segmentation of long German words into smaller units facilitated some (but not all) aspects of reading, even though these smaller words were unfamiliar to their German college student sample.

The present study cannot distinguish between these two explanations for the greater incidence of within-word refixations among both child and adult readers of English when compared with their Chinese peers. It is, indeed, possible that both factors play a role. The different patterns of developmental trajectories and cross-language differences for these different components of eye movement control do provide good evidence of the real but limited ways in which the eye movement systems tune themselves to the features of particular orthographies.

Discussion

The present study compared the developmental trajectories of reading eye movements by English- and Chinese-speaking children and adults. We will first discuss how findings from this study inform us about the development of eye movements, and then move on to issues concerning reading development in English and Chinese.

Consistency with previous results

One of the major challenges for any cross-cultural studies is to ensure the representativeness of the sample of materials and participants. We have several reasons to believe that we are reasonably close to this goal. Our English data are in line with previous eye movement studies. For example, the mean fixation duration for American third- and fifth-grade students were 263 and 244 msec, respectively. These figures were almost identical to those reported in McConkie et al. (1991), which were 262 and 243 msec, respectively. Similarly, the average saccade length for third- and fifth-grade students was 5.5, and 6.7 letters in the present study, versus 5.7 and 6.3 letters in McConkie et al. (1991). Basic parameters for English-speaking adult eye movements fall in the typical range, although the slightly shorter mean fixation duration (191 msec) and longer saccade length (10.3 letters) reflected the fact that these stories, which were intended for third- and fifth-grade students, were very easy for adult readers. Although we do not have children's figures to compare with, the Chinese adults' eye movement parameters also align well with existing data (see Feng, in press). These results, along with the good performance in reading comprehension questions, suggest that our samples – both in terms of participants and texts – are representative of respective age levels within the languages.

Development of reading eye movements

We hypothesized three possible developmental paths for reading eye movements. First, eye movements may become more efficient because of improvements in overall speed of processing or in general reading-related processes. Correspondingly, there would be no differences in eye movements in reading different orthographies. Alternatively, the mechanism that controls reading eye movements may be orthography-specific, particularly for beginning readers who are yet to be freed from effortful word recognition processes. If this is the case, we should observe distinct eye movement patterns among young readers of English and Chinese. Last but not least, different components of the eye movement mechanism may follow distinct developmental patterns, some of which language-specific and others language-universal.

Results from the present study provide unequivocal support for the last model. Clearly, different eye movement parameters follow different developmental trajectories; three patterns emerge from the data.

1. Various saccade-related measures continue to develop throughout elementary school, and show considerable differences between English- and Chinese-speaking readers. Consistent with previous research (Fischer et al., 1997; Klein & Foerster, 2001), this suggests that voluntary control in the <u>where</u> system is linked to the development of cognitive processes – in this case increasingly proficient reading processes. Consequently, differences in saccade patterns reflect different perceptual and cognitive demands Chinese and English reading imposes on the reader. This will be further elaborated in the following section.

2. Beginning readers make higher proportions of long fixations; this pattern is invariant across the two languages, suggesting a universal developmental trend. Although the present study cannot rule out the possibility that this is due to maturation, a recent theory sheds light on the nature of the phenomenon. In their <u>Competition-Inhibition</u> theory, Yang and McConkie (2001) proposed that fixation duration during reading is determined by the competition between two brain centers (the <u>fixate</u> center and the <u>move</u> center). In most cases fixation duration is determined by the relatively autonomous interaction between these two centers, but when necessary, for example when comprehension difficulties occur, the cognitive process may intervene by changing the

interaction between the two centers and thus extend the current fixation. Assuming beginning readers encounter more difficulties in reading, the Competition-Inhibition theory predicts more cognitive intervention and thus a higher proportion of long fixations. To the extent that the above assumption is true in both English and Chinese reading, the theory also nicely accounts for the lack of language differences in the developmental pattern of fixation durations.

3. Distributions of fixation duration reveal that, with the exception of long fixations discussed above, the basic mechanism for fixation control appears to be stable across age and language. This finding corroborates observations from fixation duration distributions in McConkie et al. (1991). It is also consistent with Fischer et al.'s (1997) conclusion that the neurological mechanism that controls fixation duration (the <u>when</u> system) develops early and is mature by school age. Thus, evidence from this and other studies suggests that (a) the development of fixation duration control is primarily a maturational process that is accomplished by the time children learn to read, and (b) experiential factors (such as reading experience or orthography) have limited influence on this process.

The above conclusion may appear to be in conflict with the notion that fixation duration reflects moment-by-moment cognitive processes in reading (Rayner, 1998; Reichle et al., 1998, 2003). Two clarifications help to resolve the paradox. First, our data support the notion that cognitive processes affect eye movement planning in real time. The data also suggest that the cognitive influence may be limited to some fixations, leaving other fixations controlled by autonomous oculomotor processes (c.f., Yang & McConkie, 2001). Furthermore, it is worth noting that the claim that eye movements reflect moment-to-moment processing is often based on mean fixation duration, which includes autonomously generated fixations as well as those involving cognitive control (see Yang & McConkie, 2001). Statistical analyses comparing fixation duration across experimental conditions tend to highlight the effect of cognition, because autonomous processes are not likely to differ across experimental manipulations. An empirical example can be found in Feng et al. (2001), which compared fixation duration on words that violated phonological and contextual expectation in reading. Distribution functions, presented as survival curves, showed that most, if not all, of the statistically significant differences across conditions were concentrated at the right tails of the distributions, i.e. with long fixations. Traditional linear statistics are not designed to detect situations such as this. Hence, while there is no doubt that high level cognitive and linguistic processes play important roles in determining fixation duration in reading, the basic neurological mechanism that determines the length of fixations appears to be robust and autonomous when children start to learn to read (see also Fischer et al., 1997; McConkie et al., 1991).

The existence of three distinct development trajectories in reading eye movements calls for a theory of the development of reading eye movement control. Findings from the present study rule out the simplistic notion that all aspects of reading eye movements continue to improve with age and reading experience. In the remainder of this paper, we will provide an initial sketch of a model of reading eye movement development that is consistent with observations from this and prior studies (e.g., McConkie et al., 1991).

We speculate that a beginning reader is equipped with the basic oculomotor abilities – to maintain fixations and to plan and execute saccades to selected targets – that are mature and autonomous. This seems to be a safe assumption given that a typical 6 year old should already have made well over 120 million eye movements (assuming two eye-movements per second and an average of eight hours of wakeful time per day) This is also consistent with the finding in McConkie et al. (1991) that first grade students follow the same oculomotor strategies in targeting words as adult readers. The present study and Fischer et al. (1997) provide evidence that basic fixation duration control is mature by around the time children start to read.

In addition, children have some cognitive control over these oculomotor functions, although the extent to which cognitive processes can overwrite the default oculomotor programs vary with age, the oculomotor function to be controlled, and the nature of the cognitive processes involved. With regard to age, Fischer et al. (1997) found that adults and older children are faster and better at inhibiting reflexive oculomotor programming; this should extend naturally to reading. Furthermore, both Fischer et al. and our data suggest that the when system that controls fixation duration is less susceptible to cognitive control than the where system that is responsible for determining saccade targets. Thus, larger developmental and orthographic differences are observed in saccade-related measures than in fixation duration. Finally, the driving force behind most developmental changes in reading eye movements is likely to be changes in reading processes that reflect improved reading proficiency. Because processes such as word recognition and text comprehension are highly efficient and automated among skilled readers, there is less need for higher level processes to override default oculomotor programs, which provides an explanation for the remarkable similarities in the eye movements of skilled English- and Chinese readers.

Reading is a complex process that involves the interaction of a host of perceptual, linguistic, and cognitive factors. Anyone who has read this article to the end surely qualifies as an expert in the coordination of these processes. This very expertise makes disentangling the components of reading difficult. We hope we have shown that developmental data, and particularly the consideration of developmental trajectories among different components of the reading process, can help make clear the ways in which maturational, linguistic, and experiential processes interact to produce skilled reading.

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Appendix A. Reading Materials

Language	Story	# of words (char)	Word length	Grade 3	Grade 5	Adults
English	BOAT	60	5.35	X	X	X
	MULE	222	5.65	X	X	X
	BASKETBALL	87	5.40	X		X
	BEES	264	4.90	X		X
	GOODALL	385	5.65	X		X
	CELL	108	6.32		X	X
	MOZART	249	5.07		X	X
	NEWTON	429	5.96		X	X
Chinese	BOAT	61 (83)	1.62	X	X	X
	MULE	196 (250)	1.56	X	X	X
	BASKETBALL	68 (83)	1.48	X		X
	FISH	190 (234)	1.55	X		X
	MAO	304 (426)	1.54	X		X
	SWALLOW	129 (162)	1.67		X	X
	WU	248 (311)	1.57		X	X
	QIAN	349 (534)	1.70		X	X

Note: Further information about the reading materials is provided below.

Two stories were chosen to be comparable across languages. The "Power of Boats" (BOAT, see Appendix B) was an expository text on the evolution of boat engines, translated from English to Chinese. "The Foolish Mule" (MULE) was an Aesop fable about a mule who soaked a sack of cotton when crossing a stream in hope to lessen the weight on his back. We used two roughly parallel versions of the same story in both cultures.

The rest of the stories were selected from extracurricular reading books published in China and the U.S. They were representative of readings children would naturally encounter everyday. For the English materials, BASKETBALL was a short passage about the origin of the basketball game. BEES and CELL introduced some interesting nature of honeybees and the history of the discovery of cells, respectively. GOODALL, NEWTON, and MOZART were bibliographical stories about two scientists, Jane Goodall and Sir Isaac Newton, and a musician, Wolfgang A. Mozart.

The Chinese materials were similar to the English ones in terms of contents and length. The BASKETBALL story was also about the history of basketball, though the story differed in details from the English version. The FISH and SWALLOW stories were expository pieces on deep sea fish and the migration of swallows, respectively. There were also three bibliographical stories, as in the English stories. MAO was a story about

Yisheng Mao, an architect who is known for his design of many bridges in China. QIAN was about Xuesen Qian, a well-known Chinese physicist. A story chosen to be parallel to MOZART, WU was a bibliography on Cheng'en Wu, a famous writer in Ming Dynasty who wrote the novel *XiYouJi*, whose main character, the Money King, is loved by children in China.

Appendix B. A Sample Story: The Power of Boats

The English version

Different boats use different kinds of energy for power. In the past, boats usually used sails to harness the power of the wind. Other boats had oars and needed people for power. But many improvements were made over time. The invention of the engine, for example, allowed boats to travel faster and farther. Now some boats use even better motors.

The Chinese version

各种不同的船利用不同的动力行驶。古时候，货船通常得靠帆利用风力前进，有些船需要用人力划桨。后来逐渐改进，轮船装上了烧煤的蒸汽机，船就能够驶向更遥远的陆地。现在，一部分船已经有了更好的动力了。

Figure Captions:

Figure 1. Figure 1 shows average reading time (in msec) per word for different groups of readers. American and Chinese adult readers' reading speed did not differ significantly in either measure.

Figures 2. Average number of fixations per word, based on all reading materials, for American and Chinese readers. American children made significant number of fixations than Chinese children did. Adult readers of the two languages did not differ in the number of fixations.

Figure 3. Mean fixation duration for American and Chinese readers. There are no significant differences between the two languages in 3rd and 5th grade students. American undergraduate students' fixation duration is significantly shorter than that of Chinese counterparts.

Figure 4. Frequency distributions of fixation duration. The US distributions are elevated for clarity. Language differences were minimal, with American children making slightly more short fixations than Chinese children. Chinese adults' fixations tend to be slightly longer than those of American adults. However, American and Chinese fixation durations followed qualitatively similar distribution functions – they were almost identical at the tails of the distributions, and they all peak at approximately 180 msec. In addition, developmental changes in fixation duration occurred primarily at the right tails of distributions.

Figure 5. Frequency distributions of progressive saccade lengths. Saccade length was measured in screen pixels; each letter was approximately 7.3 pixels, and each character was approximately 28.5 pixels. Distributions for Adults and Fifth grade students were elevated for clarity. Proficient readers made more long saccades and fewer short saccades. American children made many more short saccades than Chinese peers, something American adult readers did not do. In general, Chinese readers made more long saccades than American readers did.

Figures 6A-C. The probability of making a progressive saccade (Figure 6A) increased with age. American children made less progressive fixations compared to Chinese children, although adult readers of both languages did not differ in the rates of progressive fixations. The probability of refixating the same word (Figure 6B) did not differ significantly for American and Chinese adult readers, but American children were more likely to make refixations than their Chinese peers. The probability of making a regression (Figure 6C) showed a significant language difference – Chinese readers made significantly more regressions than American readers – but no significant age differences.

Figure 1. Mean Reading Time per Word

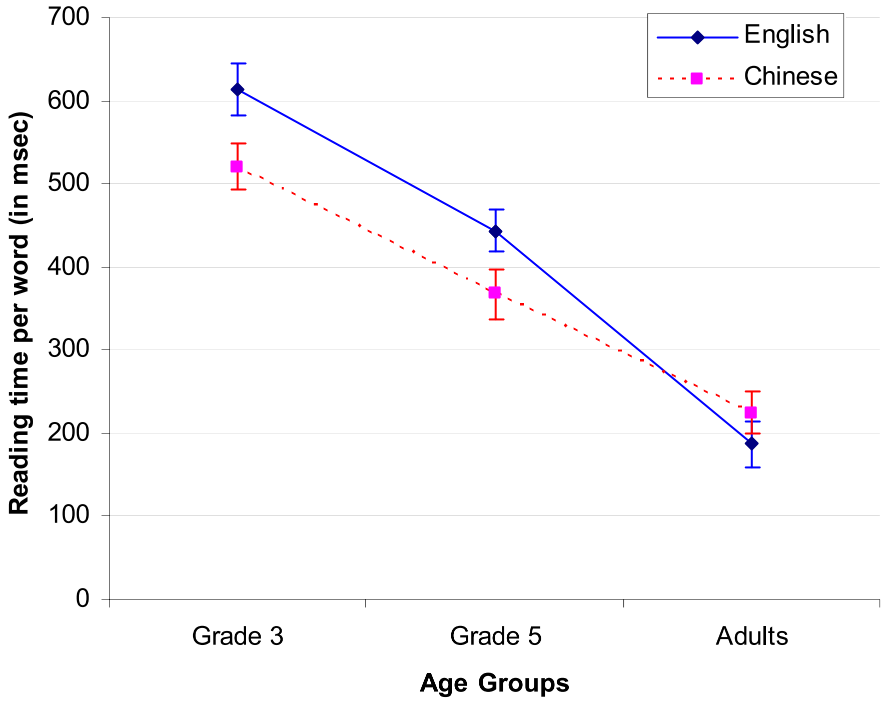
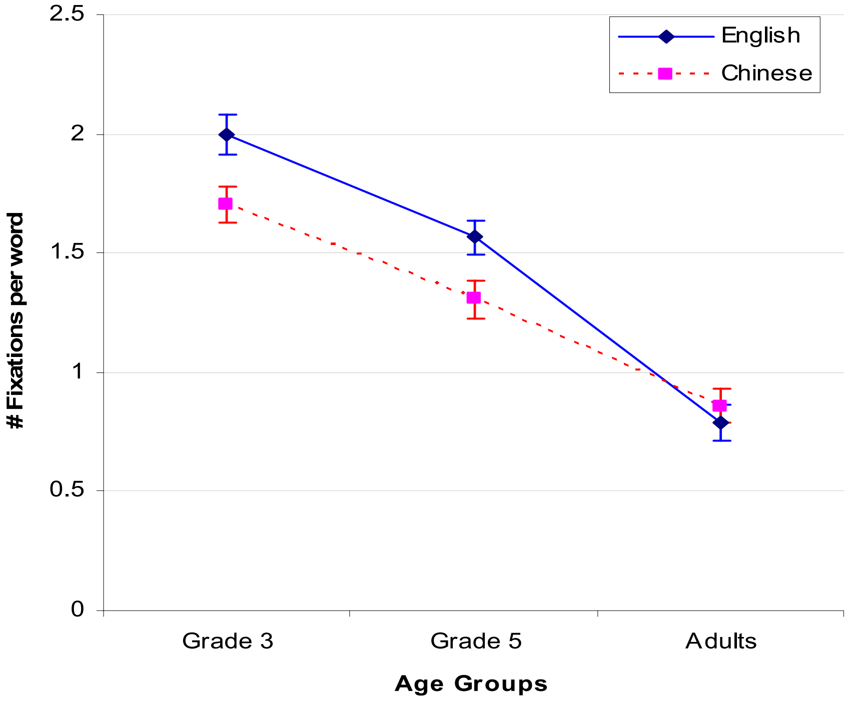


Figure 1. Figure 1 shows average reading time (in msec) per word for different groups of readers. American and Chinese adult readers' reading speed did not differ significantly in either measure.

Figure 2. Number of Fixations per Word.



Figures 2. Average number of fixations per word, based on all reading materials, for American and Chinese readers. American children made significant number of fixations than Chinese children did. Adult readers of the two languages did not differ in the number of fixations.

Figure 3. Mean Fixation Duration for American and Chinese readers.

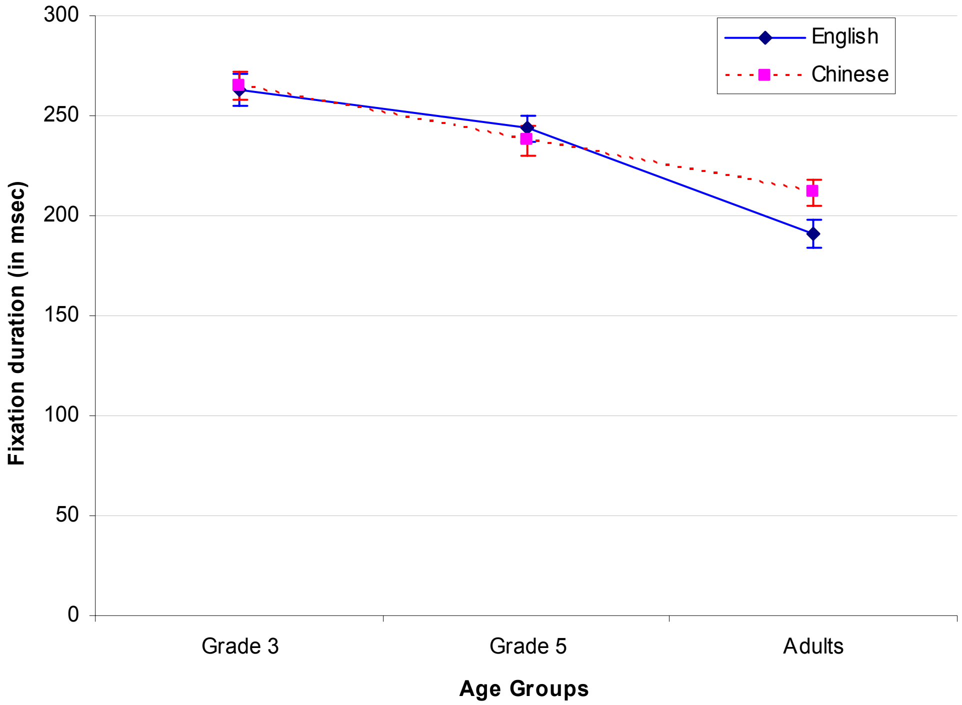


Figure 3. Mean fixation duration for American and Chinese readers. There are no significant differences between the two languages in 3rd and 5th grade students. American undergraduate students' fixation duration is significantly shorter than that of Chinese counterparts.

Figure 43. Frequency Distributions of Fixation Durations.

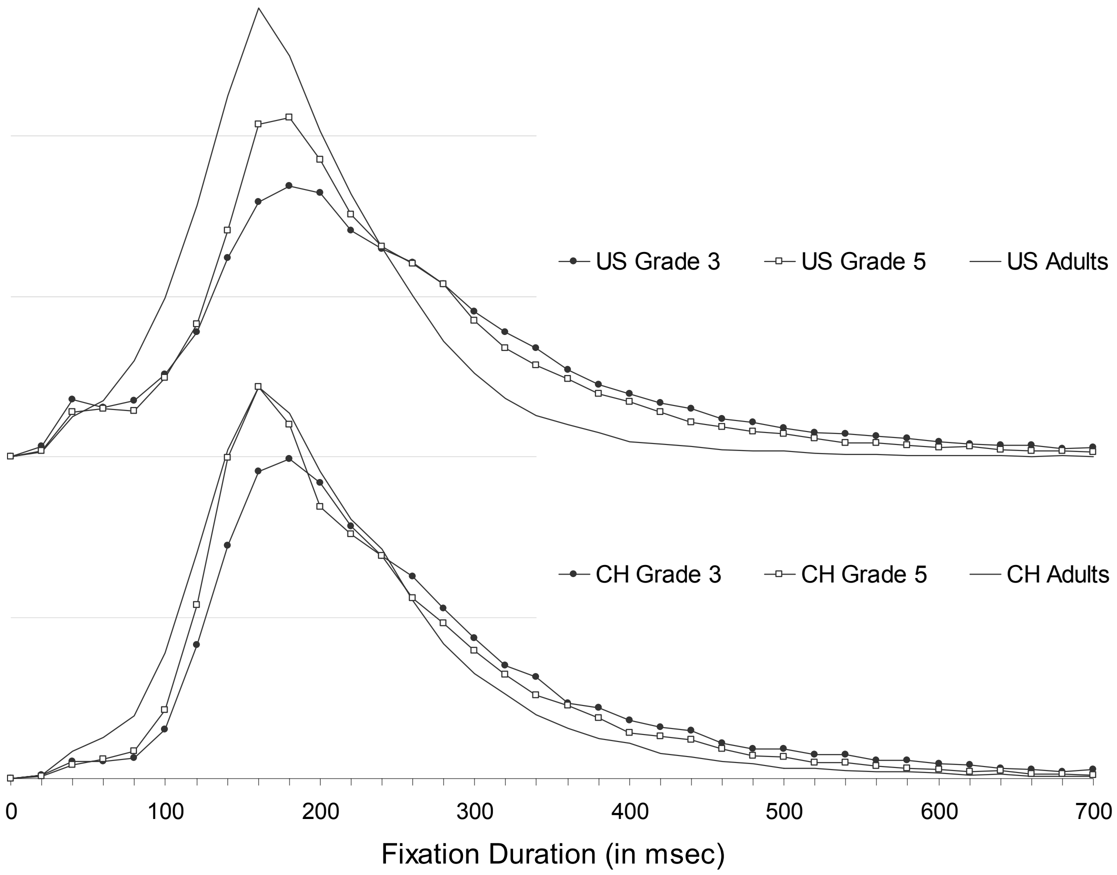


Figure 4. Frequency distributions of fixation duration. The US distributions are elevated for clarity. Language differences were minimal, with American children making slightly more short fixations than Chinese children. Chinese adults' fixations tend to be slightly longer than those of American adults. However, American and Chinese fixation durations followed qualitatively similar distribution functions – they were almost identical at the tails of the distributions, and they all peak at approximately 180 msec. In addition, developmental changes in fixation duration occurred primarily at the right tails of distributions.

Figure 5. Frequency Distributions of Saccade Length.

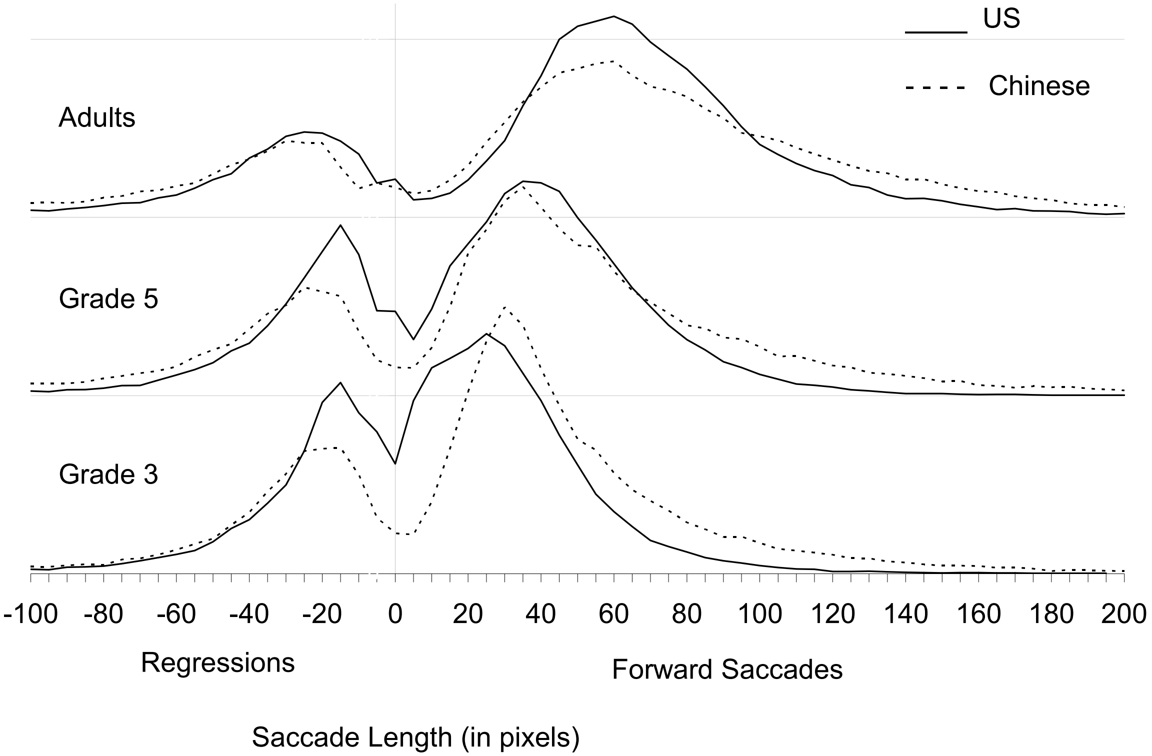
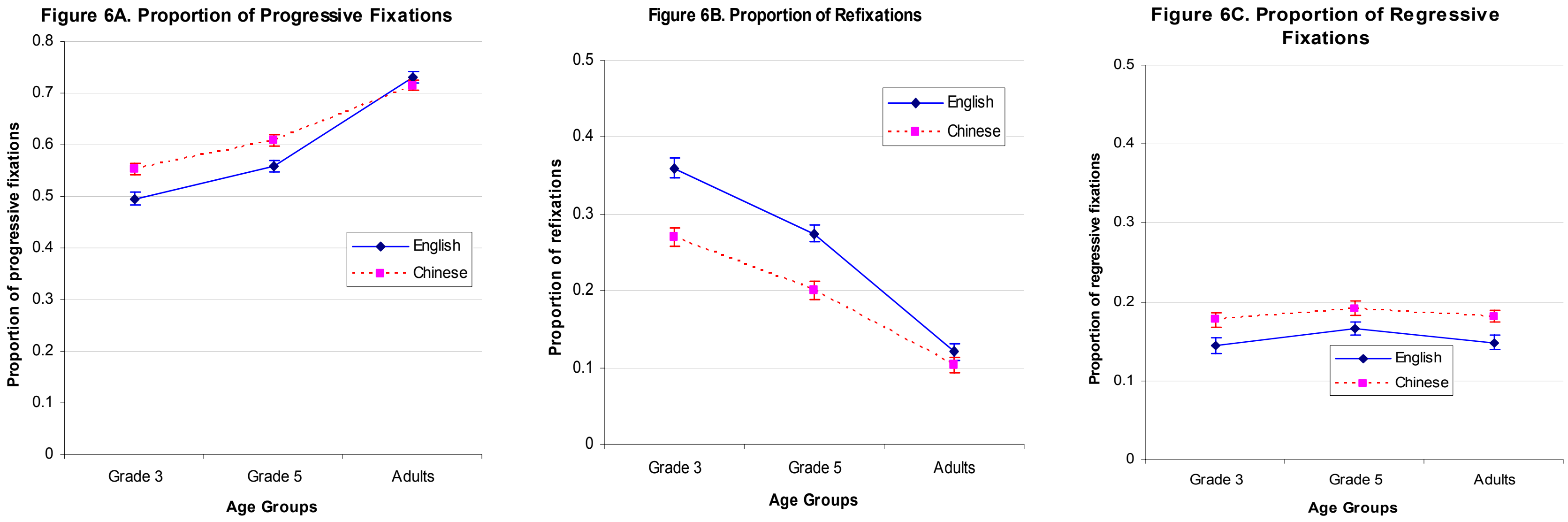


Figure 5. Frequency distributions of progressive saccade lengths. Saccade length was measured in screen pixels; each letter was approximately 7.3 pixels, and each character was approximately 28.5 pixels. Distributions for Adults and Fifth grade students were elevated for clarity. Proficient readers made more long saccades and fewer short saccades. American children made many more short saccades than Chinese peers, something American adult readers did not do. In general, Chinese readers made more long saccades than American readers did.

Figure 6. Proportions of Progressive Fixations, Regressive Fixations, and Refixations.



Figures 6A-C. The probability of making a progressive saccade (Figure 6A) increased with age. American children made less progressive fixations compared to Chinese children, although adult readers of both languages did not differ in the rates of progressive fixations. The probability of refixating the same word (Figure 6B) did not differ significantly for American and Chinese adult readers, but American children were more likely to make refixations than their Chinese peers. The probability of making a regression (Figure 6C) showed a significant language difference – Chinese readers made significantly more regressions than American readers – but no significant age differences.