Synchrony and asynchrony of the two eyes in binocular fixations in the reading of English and Chinese; the implications for ocular prevalence

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Abstract

We explore low-level, behavioural universals in reading, across English and Chinese. We investigated binocular coordination in terms of the small non-alignments between the two eyes' fixations in time. We define a typology of nine such asynchronies and report the different spatial distributions of these types across the screen of text. We interpret them in terms of their implications for *ocular prevalence*—the prioritizing of the input from one eye over the input from the other eye in higher perception/cognition, after binocular fusion. The results show striking similarities of binocular reading behaviours across the two very different orthographies. Asynchronies in which one eye begins the fixation earlier and/or ends it later occur most frequently in the hemifield corresponding to that eye. We propose that such small asynchronies in binocular fixations prioritize the higher processing of the input from that eye, after binocular fusion.

Keywords: binocular reading; eye-tracking; ocular prevalence; English; Chinese

Introduction

Two topics have attracted increasing attention from reading researchers over recent years. One is binocular coordination during reading (e.g. Liversedge, White, Findlay, & Rayner, 2006; Shillcock, Roberts, Kreiner, & Obregón, 2010); how do the two eyes coordinate their efforts? The other topic is the specific effects of different languages and their orthographies (e.g. Hsiao, Shillcock, Obregón, Kreiner, Roberts, & McDonald, 2018; Liversedge, Drieghe, Li, Yan, Bai, & Hyönä, 2016); are there universal behaviours in reading? We address both of these issues, below. We ask, first, do the small temporal asynchronies in the fixations of the two eyes have implications for changing the prioritizing of the input from one eye to the other ('ocular prevalence') in higher perception/cognition, after binocular fusion? Second, do the same behaviours have the same effects in languages with very different orthographies?

Chinese, as a logographic language, is considered to be ideographic and its written text has a high degree of visual density compared with alphabetic languages such as English (cf. Hsiao et al., 2018). The higher visual density and greater informational density of Chinese text are associated with smaller saccades and longer fixations (cf. Hsiao, 2017; Liversedge et al., 2016), compared with English. Ho and Bryant (1999) suggest different visual skills are important for learning to read English and Chinese. Similarly, McBride-Chang, Tong and Mo (2015) propose that more regions of the brain need to be co-opted during the reading of Chinese, compared with alphabetic texts.

However, despite such processing differences in English and Chinese reading, commonalities—or universals—in reading behaviours have also been proposed. Sun, Morita and Stark (1985) reported similar patterns of saccades and fixations in reading the two languages. Feng, Miller, Shu and Zhang (2009) also reported similarities between Chinese and English reading behaviours. In a recent study, Liversedge et al. (2016) reported universals in binocular eye movement behaviours (across English, Chinese and Finnish readers) concerning word frequency, word length and word predictability.

Cross-linguistic research on binocular coordination of Chinese and English has so far mainly been concerned with the basic *spatial* characteristics of eye-movement behaviours and binocular disparities during reading (e.g. Hsiao et al., 2018; Kirkby, Webster, Blythe, & Liversedge, 2008; Liversedge et al., 2006; Shillcock et al., 2010), specifying the spatial location of the two eyes' fixations. Hsiao (2017) has investigated binocular disparities with *temporally conjugate* fixations (i.e. fixations in which the right and left eye both start and end their fixations at the same time.) She reports both similarities and differences—chiefly quantitative—across the two languages.

However, *temporal disjugacy*, the unyoking of the two eyes' fixations in time, has been less explored; it provides a new perspective on eye-movements in reading. The research we report below focuses on binocular fixations of reading English and Chinese in terms of temporal asynchronies between the two eyes during multiline reading. Instead of simple, overall duration, we explore the non-alignment in the timing of the start and end points of the fixation of the two eyes.

The unequal access of the two eyes to the stimulus may have implications for *ocular prevalence*, the weighting of one eye's input over the other eye's input in processing that is accessible to consciousness, after binocular fusion (Kommerell, Schmitt, Kromeier, & Bach, 2003). Ocular prevalence is relatively evenly distributed between the two eyes: it depends on the stimulus context—one eye's input may be prevalent if the target is closer or if it is located substantially away from the midline and towards the side of the relevant eye, meaning that there will be differences in the range, clarity and distortion of the two images.

In contrast, ocular *dominance* is the tendency of the viewer to use one eye over the other in sighting tasks in which binocular fusion cannot be used because of the great difference in inputs. Such sighting situations are less frequent (although still cognitively important) than the constant demand for fusion of the two inputs. Ocular dominance is skewed towards the right eye, over the population. The implications of ocular dominance are unclear; for instance, Mapp, Ono and Barbeito (2003) have claimed that the dominant eye may have 'no unique functional role in vision'.

We tested two hypotheses: (1) The left eye will tend to begin fixating earlier and stay fixating longer in the left visual field, and the same will apply to the right eye in the right visual field, thereby facilitating the appropriate switching of ocular prevalence, even though the timing differences are small. (2) These binocular temporal asynchronies (start and end times of fixations) will be found even across the two very different orthographies of English and Chinese.

Experiment and procedure

Method

Participants 36 Chinese and 38 English native speakers, all tested and reported as having normal or corrected-to-normal vision, were paid for their participation in the experiment. They were students at the University of Edinburgh. The Chinese participants all had English as a second language. The English participants had a variety of exposures to other languages. Analysis of the role of demographic variables is ongoing.

Apparatus Participants sat in a room with diffused lighting, and watched a 22" Ilyama Vision Master Pro 514 display, at a distance of 75 cm. The screen resolution was 1024 x 768 pixels. A chin-rest and forehead support kept the head stable. The eye-tracker was an SR Research EyeLink II head-mounted video-based tracker**.**

Stimulus Materials and Procedure Eye movements were recorded binocularly with pupil and corneal reflection and sampled at 550Hz, during the reading of English (24 pt monospaced Monaco font) and Chinese (PMingLiU, standard print) texts, each comprising 21 newspaper stories, with a total of 5000 words for each language, presented in black characters on a light background, on consecutive pages with up to five left-justified lines of text each. The stimuli were intended to be comparable between languages, in form and content, based on the intuitions of native speakers. One monospaced English letter occupied 14.4 pixels; one Chinese character occupied 28 pixels. Readers were calibrated monocularly with a 9-point fixation grid while occluding the other eye with a black paper shade. Participants fixated a black fixation disc before each page of text was displayed and responded on the keyboard to a yes/no question after each story to ensure reading for meaning. The whole recording process consisted of three blocks with intervening rest-breaks, lasting for around 1.5 hours in total.

Analysis

For each binocular fixation, the start-time offset was calculated as the fixation start-time of the right eye minus the fixation start-time of the left eye. The end-time offset was calculated analogously. A difference of +/-2ms between events in the two eyes was considered as simultaneous. StartTime offset or EndTime offset < 2ms means the right eye starts or ends earlier than the left eye. StartTime offset or EndTime offset > 2ms means the left eye starts or ends earlier than the right eye.

Figure 1 shows a graphical version of the comprehensive typology of offsets. There are nine types of binocular fixation, with different patterns of start-time and end-time offsets. For example, Type 1 shows both eyes starting fixation synchronously and the left eye fixating for longer.

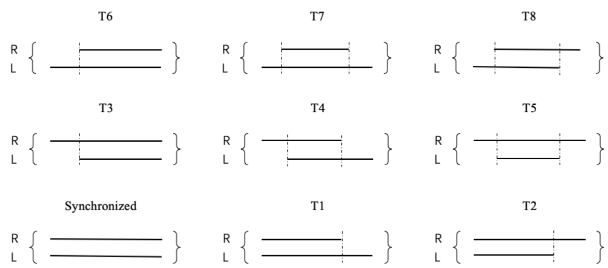

Figure 1: Typology of binocular fixation asynchronies.
Left-prevalent types: T1, T6, T7
Right-prevalent types: T2, T3, T5

We first used demonstrative graphs to show the types and their distributions on the screen. We then analysed the data quantitatively with GLMER models, to further reveal the eye-movement behaviour and potential implications for ocular prevalence during reading.

Results

We analysed a total of 160,567 binocular fixations (i.e. pairs of individual, overlapping fixations by the left and right eye) for the English readers and 158,794 binocular fixations for the Chinese readers. Below, we first report descriptive statistics from two perspectives: (a) the overall distribution of the different types in the two languages; (b) the spatial distribution of the types across the screen on which the text stimuli were displayed. Then, we report the quantitative analysis from GLMER models to explore screen differences under the main asynchronised types (i.e.T1,T2,T3,T6), based on the features shown by the descriptive analysis. The results all together indicate a lawful mapping of binocular behaviours relevant to ocular prevalence, across the visual field.

Overall results

Figure 2 shows the overall distribution of each type and their percentages among all fixation pairs for English and Chinese readers respectively. Similar patterns obtain for both languages, with notable distributions of the synchronized pairs, and Type 3 and Type 6, as the three most numerous types of binocular fixation; in particular, synchronized binocular fixations account for over half the binocular fixations for both languages. Overall the two distributions are strikingly similar. Just over 80% of binocular fixations in both languages end synchronously.

Spatial distribution

Figure 3 shows the spatial distribution of each type on the screen in English readers. The hexbin graph shows the mean coordinates (during the fixation) of the right eye for each binocular fixation, accurately representing the spatial distribution of binocular fixations. For present purposes, the choice of the right eye over the left has no implications. Readers fixated a square at the bottom right of each page

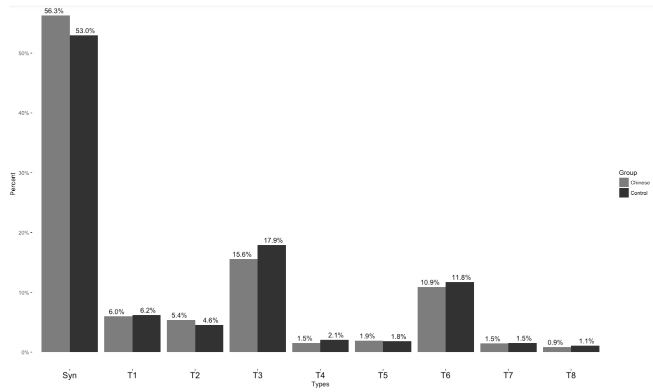

Figure 2: The distribution of types of asynchrony in English and Chinese readers

after finishing reading it. The counts indicate the frequency of fixations and the legend reflects the frequency from low to high.

The fixation pairs Syn (synchronized), T3 and T6 show the greatest density according to their numbers in the data frame. There are notable differences between left, middle and right side of the screen. Syn pairs are concentrated at the beginning of each line. T3 and T6 also show skewed distributions—a concentration at the right side of each line (T3) and a focus at the beginning of each line (T6), respectively. T1 and T2 show slighter concentrations at the beginning and the end of the lines, respectively. The remaining four types reveal less skewed spatial distributions. The Chinese data qualitatively resemble the patterns found for English readers (Figure 4). We then divided the screen into left, middle and right, to investigate the implications for ocular prevalence, in the following analyses.

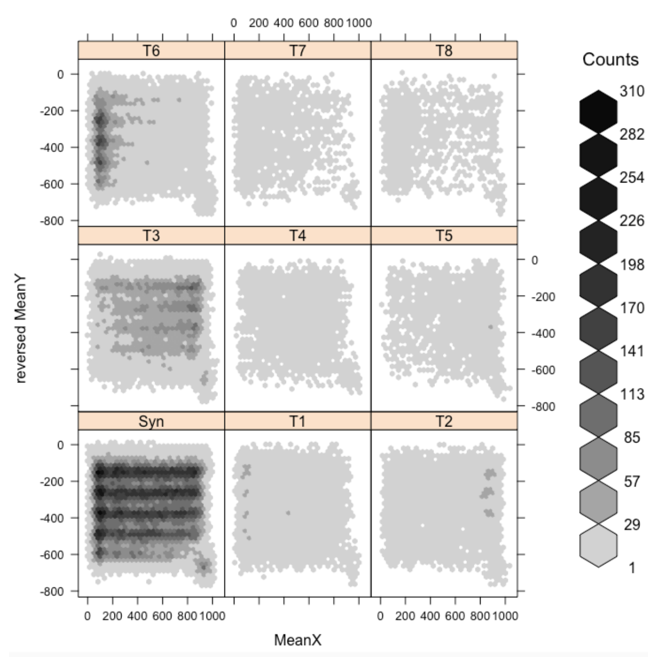

Figure 3: Spatial distribution of types in English readers.

Modeling results

In the following models, we analyse quantitatively the similarities and differences seen in the plots, with General Linear Mixed-Effects Regression Models (GLMER). All analyses were carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). We used the counts of fixation pairs as dependent variables in all the models. We defined null models with participants and pages as random factors. Predictor variables included the sides of the screen (left, middle and right) and tested under subsets of types (cf. Figure 1) in each group (English, Chinese) separately to explore the quantitative distribution of these types. All Model fit was assessed using the anova function to compare different models. Models were created to understand the statistical dimension of our descriptive data. The results show a systematic pattern of binocular behavior across languages, with the Chinese data being somewhat more systematic.

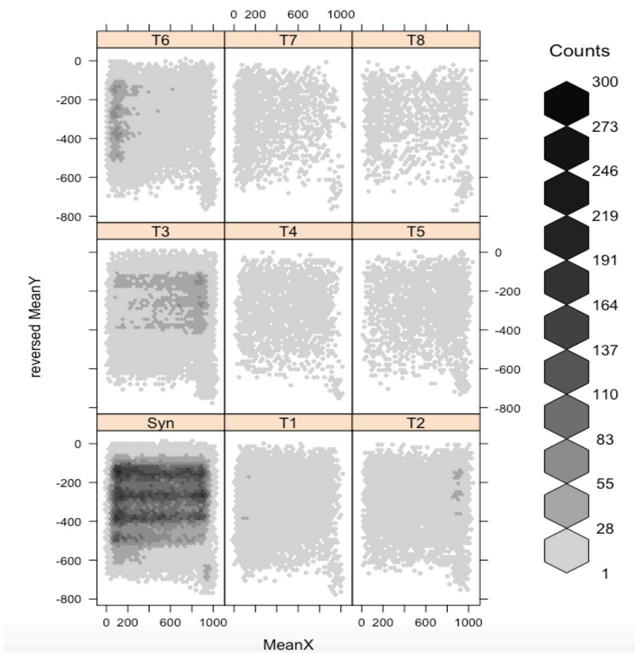

Figure 4: Spatial distribution of types in Chinese readers.

Table 1: GLMER analysis of Screen differences in English T1

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.464847	0.030979	< 2e-16 ***
Screen Left	0.003518	0.022029	0.873
Screen Right	-0.277650	0.028813	< 2e-16 ***
Random effects			
	Number	Variance	Std.dev.
Participant	38	0.02671	0.1634

Table 2: GLMER analysis of Screen differences in English T6

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.50283	0.04796	< 2e-16 ***
Screen Left	0.59289	0.01784	< 2e-16 ***
Screen Right	-0.21863	0.02523	< 2e-16 ***
Random effects			
	Number	Variance	Std.dev.
Participant	38	0.07300	0.2702
Page	113	0.01392	0.1180

The results of T1, T2, T3 and T6 which contain most of the non-Syn types are similarly distributed in both groups. The patterns reflect ocular prevalence. Firstly, Tables 1 and 2 show that T1 and T6, which have left-eye priority, have significantly less value on the right side of the screen compared with the middle (i.e. the reference) in English readers. T6 also has significantly more value on the left side. Similar results can be observed in Chinese readers as shown in Table 3 and 4, particularly in T6, though in Chinese type T1 has significantly more value on the left side, indicating a more systematic pattern across the line.

Furthermore, T2 and T3 as right-eye priority types, show significantly more value on the right side of the screen in English readers, as can be seen in Table 5 and 6, while T3 also shows significantly less value on the left side. Also, as seen in Table 7 and 8, Chinese T2 and T3 show more value on the right side. Furthermore, both types also indicate significantly less value on the left side of the screen, completing the picture of the quantitative spatial distribution of the different types.

Table 3: GLMER analysis of Screen differences in Chinese T1

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.41575	0.04005	< 2e-16 ***
Screen Left	0.12324	0.02316	1.03e-07 ***
Screen Right	-0.19722	0.02907	1.16e-11 ***
Random effects			
	Number	Variance	Std.dev.
Participant	36	0.04196	0.2048
Page	103	0.01102	0.1050

Table 4: GLMER analysis of Screen differences in Chinese T6

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.58834	0.04579	< 2e-16 ***
Screen Left	0.48823	0.01733	< 2e-16 ***
Screen Right	-0.11661	0.01303	1.16e-07 ***
Random effects			
	Number	Variance	Std.dev.
Participant	36	0.06581	0.2565
Page	103	0.02820	0.1679

Table 5: GLMER analysis of Screen differences in English T2

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.25171	0.03118	6.82e-16 ***
Screen Left	0.02285	0.03225	0.479
Screen Right	0.12263	0.02928	2.81e-05 ***
Random effects			
	Number	Variance	Std.dev.
Participant	38	0.01415	0.1189

Table 6: GLMER analysis of Screen differences in English T3

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	1.02541	0.04652	< 2e-16 ***
Screen Left	-0.37914	0.01568	< 2e-16 ***
Screen Right	0.03450	0.01340	0.01 *
Random effects			
	Number	Variance	Std.dev.
Participant	38	0.07089	0.2662
Page	113	0.02240	0.1497

Table 7: GLMER analysis of Screen differences in Chinese T2

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.32966	0.03894	< 2e-16 ***
Screen Left	-0.06823	0.03125	0.029 *
Screen Right	0.21347	0.02598	< 2e-16 ***
Random effects			
	Number	Variance	Std.dev.
Participant	36	0.03472	0.18634
Page	103	0.00578	0.07602

Table 8: GLMER analysis of Screen differences in Chinese T3

Fixed effects			
	Estimate	SE	Pr(>|z|)
(Intercept)	0.89793	0.04998	< 2e-16 ***
Screen Left	-0.13152	0.01665	2.85e-15 ***
Screen Right	0.13598	0.01486	< 2e-16 ***
Random effects			
	Number	Variance	Std.dev.
Participant	36	0.07427	0.2725
Page	103	0.03125	0.1768

This systematic binocular pattern, further shows in T5 and T7 in both readers, which are right-eye priority and left-eye priority respectively, though the data are relatively sparse. We find significantly more value at the right side compared with the middle in Chinese T5 (Est= 0.14502, SE= 0.04432, z(3070)= 3.272, $p < .01$) and significantly more value at the left side compared with the middle in Chinese T7 (Est= 0.16563, SE= 0.05074, z(2349)= 3.264, $p < .01$). Similar results also show in English T5 (Est= 0.10911, SE= 0.04554, z(2939)= 2.396, $p < .05$) and English T7 (Est= 0.14013, SE= 0.04778, z(2436)= 2.933, $p < .01$), which all accord with the previous results.

Discussion

Overall, we have found that the asynchronies of binocular fixation accord with ocular prevalence. When readers fixate towards the left, the left eye tends to be prioritized in starting and ending fixations, and conversely for the right eye for rightward fixations. Statistical modelling tends to bear out the picture seen in Figures 3 and 4. The left-to-right dimension of the text was only approximated by our division of the space into three; consequently, the statistical modelling can show the concentration of a particular type on the right side of the screen by a significant reduction in the number of types from the middle section to the right section. Overall, we have found qualitatively similar results from English and Chinese readers, with the latter showing a more systematic picture.

Both orthographies are left-to-right. One way to understand the results is that for fixations on the left, the left eye had tended to travel faster than the right eye and thus arrive earlier to start the fixation. The return sweep from the end of one line to the beginning of the next is a prime candidate for this effect. Smaller, regressive eye movements on the same line are a further candidate. The return sweep involves the left eye's lateral rectus muscle, associated with faster acceleration (Robinson, 1964); the left eye gets there first.

The lateral rectus muscle is critical for *abductive* saccades—moving away from the nose. Its relative strength over the musculature controlling *adductive* saccades (towards the nose) provides us with a more general explanation for the overall pattern in our data. Thus, left-to-right movements across the line of text will favour the right eye which moves abductively and will tend to arrive earlier to start the fixation, particularly for longer saccades landing more towards the end of the line. T3 (more numerous), T4 and T5 are the early-right-priority types. We suggest that an earlier start to a fixation, even by a small margin, constitutes a stimulus for ocular prevalence. The right eye tends to assume priority in the conscious perception of the text as the reader moves from left to right across the screen. Types T6, T7 and T8 are the early-left-priority types; the picture is clearest in the more numerous T6.

The other aspect of asynchrony is late-priority, when one eye continues to fixate for longer. T2 (more numerous), T5 and T8 are the late-right priority types, tending to be associated with the right side of the screen. T1 (more numerous), T4 and T7 are the late-left-priority types, tending to be associated with the left of the screen. Overall, the left eye has earlier starts and/or later ends on the left of the screen. Conversely, the right eye, tends to have earlier starts and/or later ends on the right side of the screen.

One eye continuing to fixate longer can also cue a switch in ocular prevalence or confirm an existing prevalence. In a fixation preceding a return sweep, an extended right-eye fixation may reflect a faster abductive beginning to the saccade by the left eye.

The differences between English and Chinese readers on T1 and T3 implies more systematic binocular behaviour by Chinese readers. In accordance with the binocular pattern, T1 as left-eye-prevalent type concentrates on the left side and T3 as right-eye-prevalent type concentrates on the right side spatially in both readers. However, while the model of T1 in English readers (Table 1) only shows a significantly smaller distribution on the right, the model for the Chinese readers (Table 3) shows a significantly greater distribution on the left as well as a smaller one on the right. Similarly, the distribution of T5 and T7 which are right-eye-prevalent and left-eye-prevalent types shows significantly greater numbers at the right side and left side respectively only in Chinese readers, while not significant at all in English readers.

In general, the patterns predicted by ocular prevalence were well supported in both languages, though Chinese shows more systematic patterns, with significantly more at the left side of T1 and significantly less at the left side of T2. This might be related to orthographic differences between the two languages, with the Chinese text filling each line with evenly spaced characters, effectively right-justifying each line. Chinese readers proceed in asynchronised manner further across each line, into the visual hemifield in which the right eye is prioritized.

The temporal asynchronies we have measured are typically very small, consisting of a few milliseconds. First, the measurements necessarily depend on Eyelink II technology and the algorithm for calculating saccade onset and offset; are the differences 'artefactual' in some way? Second, are such small differences relevant to processing? These are related questions. Understanding the process of saccade onset and offset is an ongoing research question (e.g. Bao, 2019; Hooge, Hessels, & Nyström, 2019; Hooge, Holmqvist, & Nyström, 2016; Hooge, Nyström, Cornelissen, & Holmqvist, 2015). It raises questions like: What types of visual processing occur at what times? Is there differential processing of high and low spatial frequencies, for instance, or of different colours? Further, the potential importance of a timing difference close to the sensorium is not best seen in the light of timed behaviours in psychological tasks, where small differences can be seen as inconsequential. Rather, it is a *computational* issue and the evidence is that spike-timing-dependent processing can play a key role in learning (cf. Hopfield & Brody, 2004). Small differences can have big effects.

For now, we report a predictable, interpretable pattern of temporal asynchronies arising from the mechanics of saccades. We propose that these asynchronies are informative enough to drive ocular prevalence, such that the input to the left and right eye is respectively prioritised in the higher binocularly-fused processing of the left and right visual field.

Conclusion

We have analysed small timing mismatches between the two eyes at the start and end of binocular fixations in English and Chinese reading. We have shown that such asynchronies are predictive of *ocular prevalence*, in which the input to the left eye is prioritized in conscious perception of a fused visual stimulus for targets in the left visual field and right-eye input is prioritized for targets in the right visual field. Ocular prevalence optimizes perception by respecting the differences in distortion and range for the images in the two eyes. Having one eye's fixation *begin* even slightly earlier is a way of eliciting prevalence for that input in higher perception and cognition. Having one eye's fixation *end* even slightly later is also a way of eliciting a switch in prevalence or of respecting its existing prevalence. We have shown the distribution of types of asynchrony is strikingly similar in Chinese and English. This similarity confirms our suggestion that these behaviours associated with binocular reading are oculomotor *universals*; that is, they can be taken as applying across all readers and all (left-to-right) orthographies. In ongoing research, we further analyse the quantitative differences in the distributions of the different types of asynchrony in Chinese and English, and we report the situation in right-to-left orthographies. By affecting ocular prevalence, low-level oculomotor universals can thus interact with other higher-level universals in cognitive processing.

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