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Attention Shifting During the Reading of Chinese Sentences

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An eye-movement-contingent probe detection task was used to determine the allocation of visual attention during Chinese reading. On a subset of trials, a to-be-detected visual probe replaced visual text when the eyes crossed and landed to the right of an invisible interword boundary. The probe was either near the fixated location or at a more distant location in the right or left visual field. Probe detection latencies were shorter for probes that were closer to fixation, and they were shorter when the probes were shown in the right rather than the left visual field when word order progressed from left to right. A right visual field advantage also emerged when word order was reversed and progressed from right to left. These results indicate that the direction of shifts of attention is preset and progresses with a script-specific word order. This directional bias can account for asymmetric extensions of the perceptual span toward upcoming words during normal reading.

Public Significance Statement

We found that more attention was deployed in the right rather than that in the left visual field during reading. This is consistent with the finding that the perceptual span is asymmetrical toward the reading direction. We also found that shift direction is not set during individual reading directions. Instead, shift direction appears to be set automatically for a particular writing system. The findings in our study will contribute to the understanding of the attention allocation during reading and the development of eye movement control models.

Keywords: reading, attention, eye movements, perceptual span

Peripherally and parafoveally appearing visual stimuli have shorter detection and classification latencies when they appear at a location that is the target of a saccadic eye movement (Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995). Similarly, reaction times (RT) to stimuli have shorter latencies when they appear at cued locations while the eyes are kept fixated, presumably because cuing is used for a covert shifting of attention to the marked location (Posner, 1978, 1980; Rizzolatti, Riggio, Dascola, & Umiltá, 1987). Although effects of eye movement targeting and of attention shifting can be dissociated (Wollenberg, Deubel, & Szinte, 2018), cognitively guided (endogenous) shifts of attention and saccade programming are generally closely coordinated and functionally related (Findlay, 2009; Klein, 1994; Posner, 1980), and their programming is supported by overlapping neural structures (Beauchamp, Petit, Ellmore, Ingeholm, & Haxby, 2001).

Asymmetries in the perceptual span during fluent reading have been used as evidence for the assumption that the programming of overt eye movements and the covert shifting of attention are closely linked in this task and that shifts of attention progress with word order (Rayner, 1998, 2009). In these studies, eye-movement-contingent windows, with legible text inside and degraded or masked text outside the window, were used to manipulate the spatial area of text from which useful linguistic information could be extracted (McConkie & Rayner, 1975). No viewing constraints were applied in a control condition, and the perceptual span was

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defined as the smallest window size that enabled normal reading, that is, the smallest window size that matched performance in the control condition.

The results have consistently shown that the span is extended in the direction of upcoming words. For readers of left-to-right ordered English and Chinese scripts, the span is thus asymmetrically extended toward the right relative to a fixation location (Inhoff & Liu, 1998; McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980; Yan, Zhou, Shu, & Kliegl, 2015), and for readers of right-to-left ordered Hebrew, Arabic, and Urdu scripts, it is extended toward the left (Jordan et al., 2014; Pollatsek, Bolozky, Well, & Rayner, 1981; Paterson et al., 2014). The asymmetry of the perceptual span toward upcoming words even emerges in a vertical direction, when traditional Chinese script is ordered in a familiar top-to-bottom order (Yan, Pan, Chang, & Kliegl, 2019).

The extent to which endogenous shifts of attention depend on task demands is unclear, however. In typical attention shift studies, the experimental task requires the detection or classification of simple objects in the periphery, and a small number of attention shifts, typically just one, is to be executed from a standardized starting position, typically a fixation location near the center of display screen. On the following trial, attention is typically shifted to a location that is unrelated to the target location of the preceding trial. During reading, by contrast, attention needs to be shifted multiple times along a sequence of words, each time from a different starting position. Moreover, successive shifts of attention are not independent of each other but constrained by word order. Consequently, shifts of attention during reading could differ from endogenous shifts of attention in other experimental tasks.

The current study sought to distinguish two theoretical claims. According to one, the processing of an attended word controls the initiation of an endogenous shift of attention toward a to-be-identified word, generally the next word in the text. In the reading task, this shift occurs before a corresponding saccade is executed, and this extends the perceptual span in the direction of reading. Alternatively, it is also possible that there may be no endogenous shifts of attention during reading fixations. Instead, effective viewing windows are asymmetric because the masking of previously fixated (and already identified) words is less detrimental to reading than the masking of to-be-identified words. When reading in a familiar left-to-right direction, the viewing of upcoming words to the right of fixation thus conveys more useful information than the viewing of already identified words to the left of fixation. In general, a window of legible text that reveals to-be-identified text and degrades previously identified words should result in a more fluent reading of text than a window that reveals previously identified words and degrades upcoming text.

To dissociate effects of attention shifting from effects of linguistic information extraction, we combined the reading task with a probe detection task. On a subset of trials, the execution of a saccade across and landing to the right of an invisible spatial boundary was used to replace the visible (to-be-read) Chinese sentence with a to-be-detected visual probe. This probe was shown near the postsaccadic landing position or at various distances to the right or left of it. Only the probe was visible, and readers were instructed to respond to its onset with a manual detection response. If attention was shifted with word order toward upcoming words, then RTs should be relatively short for probes that appeared near the fixated location and to the right of it. If it was the usefulness of visible information that determined information extraction, then the detection of probes in the right and left visual field should be equally effective since linguistic information is no longer visible when the probe is presented.

An earlier study (Fischer, 1999) had used a probe detection task to investigate attention shifting during reading. To-be-read sentences contained a critical word sequence, and saccades that crossed an invisible spatial boundary near the first critical word triggered the presentation of a visual probe either after a short (25 ms) or a long (170 ms) delay. Probes were presented at one of five positions relative to the landing position (-10, -5, F, $+5$, and $+10$ characters from fixation (F); minus and plus signs indicate left- and right-of-fixation locations, respectively). The results showed a robust effect of probe delay, with shorter RTs in the long delay condition. However, probes near the fixation location (F) were not detected more effectively than probes at other locations, and RTs for probes that were presented to the right and left of the fixation did not differ. These findings suggest that shifts of attention were not guided by the order of visible words.

Alternatively, the approach may not have been sensitive to effects of attention shifting. Probes appeared slightly above the text, and the full sentences remained visible throughout a trial. Consequently, the reading of visible text could have competed with probe detection, and this could have hampered the shifting of attention to the probe, irrespective of its location. The effects of probe delay are consistent with this view. According to the E-Z Reader model, the extraction of linguistic information from fixated text occurs primarily after the onset of a fixation (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; Reichle, Pollatsek, & Rayner, 2006; see also Rayner, Liversedge, & White, 2006), and the competition between text and the probe for attention may have been stronger in the short than the long delay condition.

Experiment 1

In Experiment 1, we used a modified version of Fischer's (1999) probe detection task to determine whether asymmetries in the perceptual span during reading are due to shifts of attention toward upcoming words. Novel to our approach was the dissociation of the text processing task from the probe detection task. On a subset of trials, a saccadic eye movement crossed and landed to the right of an invisible interword boundary, and this replaced the sentence with a visual probe. Since only the probe was visible, its detection should no longer be influenced by the demands of linguistic information extraction. The probe could occupy the fixated location or various locations in the right or left visual field. If the shifting of attention progressed with word order, then congruent shifts to probes in the right visual field should be executed faster than incongruent shifts to probes in the left visual field.

Method

Participants. Forty-two undergraduate or graduate students (average age was 21, including 26 females) from the universities around the Institute of Psychology, Chinese Academy of Sciences participated in this experiment. They were native Chinese speakers who had normal or corrected-to-normal vision. Participants provided written consent in accordance with the protocols approved by the ethics committee of the Institute of Psychology, Chinese Academy of Sciences. As indicated by Brysbaert and Stevens (2018), the power of mixed effects models is influenced by both participant number and item number in each condition. As their simulation results showed, 1,600 observations per condition in designs with repeated measures could detect a relatively small standardized effect size of around $d = .1$ with a power of .80. In our study, there were 40 items in each condition, and we tested 42 participants, thus there were 1,680 observations for each condition, and the design was expected to have sufficient power for the detection of even relatively small experimental effects.

Apparatus. The sentences were displayed on a 21-in. CRT monitor with a refresh rate of 150 Hz and a resolution of 1,024 × 768 pixels. The characters were shown in Song 24 font in black color (RGB: 0, 0, 0) on the white background (RGB: 255, 255, 255). The participants were seated 58 cm away from the screen; one character in the sentences subtended one degree of visual angle. Eye movements were monitored by an Eyelink 1000 eye tracking system with a sampling rate of 1,000 Hz.

Materials and procedure. There were 420 experimental sentences and another 140 fully visible filler sentences that were followed by a multiple-choice question. The length of the sentences at the onset of sentence reading varied from 21 to 27 characters (with an average length of 24). A gaze-contingent boundary paradigm was used to remove a visible experimental sentence from the screen when the location of the fixation was detected after the eyes crossed an invisible interword boundary. The boundaries were located after about the ninth character in the sentences, so that they were neither located within the first four characters nor within the last four characters of a sentence. Among the 280 sentences, 78 prior-boundary words were one character long, 171 were two characters long, 18 were three characters long, and 13 were four characters long. 90 postboundary words were one character long, 167 were two characters long, 15 were three character long, and 8 were four characters long. On 280 of the 420 trials, when the fixation was detected after the eyes crossed the boundary, the sentences would disappear from the screen immediately, then a red probe (approximately 0.3° visual angle, see Figure 1 for a sequence of this procedure) was presented around the fixation location. On the remaining trials, no probe was present after the sentence disappeared. The probe target was presented equally often at one of the seven positions: the fixated location (F) and the first-, second-, or third- character position to its left or right (referred to L3, L2, L1, *F*, R1, R2, R3, respectively for characters from left to right). The seven display conditions were counterbalanced across items and participants.

The eye tracking system was calibrated in a three-point calibration procedure at the beginning of the experiment until the maximal error of the validation was less than 0.5° visual angle and was calibrated again when needed. The participants were instructed to read and comprehend the sentences displayed on the screen. When a sentence disappeared, they were asked to press a button on the button box to indicate as quickly as possible whether there was a red target or not. They were asked to press a button on the right with the right hand if the target was present, and press a button on the left with the left hand if the target was absent. The filler sentences were fully visible, and their reading was followed by multiple-choice comprehension questions to indicate whether they read carefully and understood the sentences. The experiment lasted for about 80 min.

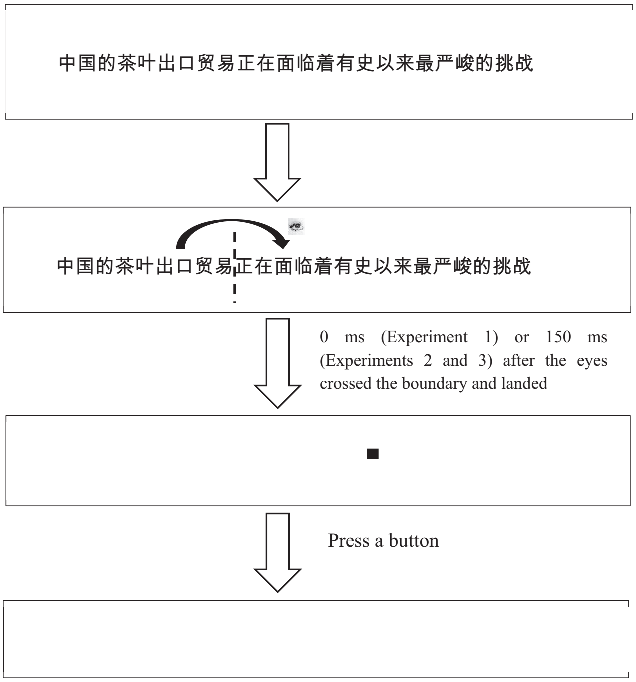

Figure 1. An illustration of the display change sequence. The sentence in this example means "The export of tea in China is now facing the biggest challenge in history."

The display change was designed to occur immediately after the postboundary fixation was detected. However, there was some delay due to the time needed to detect the transition from the end of the boundary-crossing saccade to the beginning of the following fixation, computation latency, and the time needed to replot the screen with a target symbol. Post hoc analyses showed that average interval duration between the boundary crossing and the detection of a fixation onset was 16.31 ms ($SD = 9.11$ms, min = 1 ms, max = 201 ms). The average latency between fixation onset and probe onset was 45.76 ms ($SD = 7.75$ ms, min = 35 ms, and max = 64 ms)[1].

Data Selection and Statistical Analysis

The accuracy of sentence comprehension questions was high (97%), indicating that participants paid attention on text and read for meaning. An inspection of the distribution of probe detection RTs showed a strong positive skewing (we will discuss this issue later), and outliers were removed in two steps (Baayen & Milin, 2010). The first step preceded the analysis of data. It entailed the removal of trials in which (a) the probe was not presented (0.1% trials), (b) participants pressed the wrong target present/absent button (approximately 0.8% trials), (c) RTs were extraordinarily long (>3000 ms; 0.1% trials), (d) and when there was a blink

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[1] The correlation between RTs and the fixation-to-probe delay was close to zero. When fixation-to-probe delay was added as a predictor to statistical models, its effect was negligible (See Appendix for detailed results).

during the boundary crossing saccade and when the eyes crossed the boundary due to eye drift (5.82% trials). These or relatively similar exclusion criteria are typically applied in reading studies. Together these selection criteria yielded 10,943 eligible trials. Since the distribution of these RTs was skewed to the right, log-transformations were applied to reduce skewing.

The second selection step, as recommended by Baayen and Milin (2010), entailed the pruning of the statistical model via the removal of outlier residuals. Here we used a conservative cutoff by removing scaled absolute residual values >3 (about 1% of trials). This pruning normalized the distribution of residuals but did not alter the pattern of statistical effects.

The analysis was conducted by using a linear mixed-effects model (*lme4* package, Bates, Mächler, Bolker, & Walker, 2015) in the *R* statistical software (R Core Team, 2017; see also Baayen, Davidson, & Bates, 2008). Individual (trial-based) RTs were log transformed. The fixed effects of statistical models were defined by six contrasts: (a) a foveal contrast that compared the foveal location (F) with the mean of all other locations, (b) a visual field contrast that compared the three locations to the left of fixation with the three locations to the right of fixation, (c) an eccentricity contrast that tested whether the linear trend for character locations 1, 2, and 3 differed from a slope of zero, (d) a contrast for the interaction of the linear trend of eccentricity with visual field, (e) a contrast for a quadratic trend of eccentricity, and (f) a contrast for the interaction of the quadratic trend of eccentricity with visual field (see Table 1). It should be noted that we did not have clear prediction for the last two contrasts. However, following Schad, Vasishth, Hohenstein, and Kliegl's (2020) suggestion, we added these two contrasts to increase the amount of explained variability for probe positions. Following Barr, Levy, Scheepers, and Tily (2013), we started with a maximal random factor structure, comprising intercepts for subjects and random slopes for each of the six contrasts. When a maximal model failed to converge, we used a zero-correlation parameter model and dropped random components that generated the smallest variances until the model converged.

The skewness of the residuals of the statistical model improved from 1.07 to 0.65 when a small number of outlier residuals was removed (n = 144, 1.0%) in the second step of data selection. The figures and data tables show the participant means, computed over log RTs but back-transformed to the more descriptive ms scale.

Results

Mean RTs and their standard errors are shown as a function of probe location in Figure 2 and Table 2. As can be seen, there was no substantial advantage for centrally presented probes, and their mean RT (682 ms) was only marginally shorter than the mean for the other probe locations (689 ms; b = −0.012, SE = 0.006, t = −1.948, p = .051). As predicted by the attention shift account for asymmetries of the perceptual span during reading, probe detection RT was significantly shorter when probes were presented in the right than the left visual field, 681 ms and 696 ms, respectively (b = −0.025, SE = 0.005, t = −5.051, p < .001). RTs were 685 ms, 692 ms, and 689 ms for probes at character locations 1, 2, and 3, respectively, and they were not significantly different from each other (b = 0.005, SE = 0.007, t = 0.691, p = .494). The visual field by eccentricity interaction was negligible (t = −0.199, p = .844), so was the quadratic trend and its interaction with visual field (ps > .300).

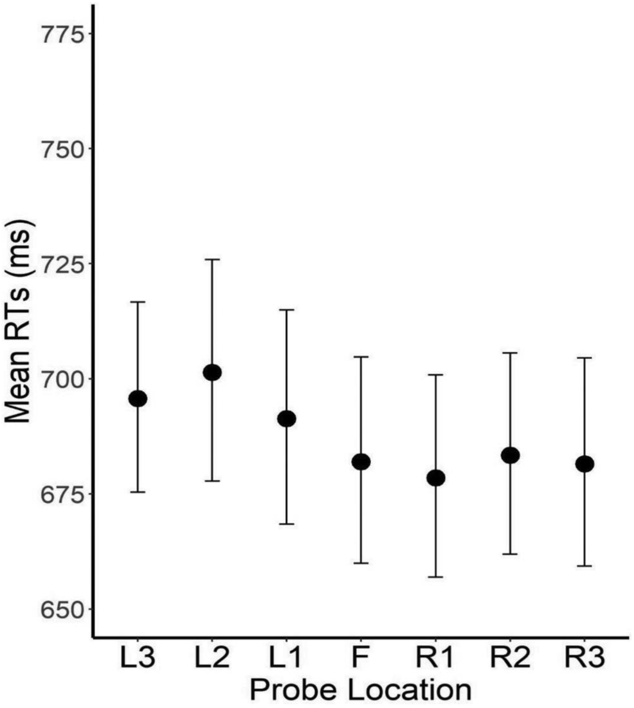

Figure 2. The mean RTs for each display condition in Experiment 1. The error bars depict the standard errors of the mean.

Post hoc Dunnett comparisons, as implemented in the *glht* function of *R* library *multcomp*, were applied to the pruned model to determine whether there was a stronger spatial bias toward the right in Experiment 1. The differences between the foveal location

Table 1
Contrast Matrix Used in the LMM Models

Contrast	F	L1	L2	L3	R1	R2	R3
Foveal	0.857	−0.143	−0.143	−0.143	−0.143	−0.143	−0.143
Visual field	0	−0.5	−0.5	−0.5	0.5	0.5	0.5
Eccentricity	0	−0.5	0	0.5	−0.5	0	0.5
Visual Field × Eccentricity	0	0.5	0	−0.5	−0.5	0	0.5
Quadratic trend	0	0.167	−0.333	0.167	0.167	−0.333	0.167
Visual Field × Quadratic	0	0.167	−0.333	0.167	−0.167	0.333	−0.167

Note. Each column in the table represents a condition regarding where the probe was presented: the fixated location (F) and the first-, second-, or third-character position to its left or right (referred to L3, L2, L1, F, R1, R2, R3, respectively for characters from left to right).

Table 2

Mean RTs (ms) of the Three Experiments When the Probes Were Presented at Seven Different Positions

Experiment	L3	L2	L1	F	R1	R2	R3
1	696	701	691	682	678	683	682
2	738	736	717	716	714	715	728
3	703	697	690	679	682	685	693

and the L2 location ($z = 3.658$, $p = .002$), and between the foveal location and the L3 location ($z = 2.796$, $p = .027$) were reliable. No other differences approached significance (all p values $> .16$).

Discussion

The main results of Experiment 1 are straightforward: When probe detection did not compete with the recognition of visible words, RTs were 15 ms shorter when a probe was presented to the right rather than to the left of fixation. Moreover, supplementary contrasts, with the foveal location as baseline, showed that RTs to the right visual field probes did not differ from the foveal baseline. RTs for foveal probes were significantly shorter, however, than for probes at the L2 and L3 locations. The detection of a probe was thus delayed when two conditions were met: when the probe's location was nonadjacent to the fixated location and when it was presented in the left visual field.

Since sentences were removed prior to the presentation of probes, the faster detection of probes in the right rather than the left visual field cannot be attributed to linguistic information extraction. Instead, the shifting of attention to probes was more effective when it was congruent than when it was incongruent with word order. This supports the view that shifts of attention contribute to the asymmetric shape of the perceptual span during reading.

As noted in the method section, the average latency between fixation onset, the average latency between fixation onset and probe onset ranged between 35 ms and 64 ms (with a mean of 45.76 ms). Some may argue that this amount of time might have been enough to process the fixated word, and attention had already moved to word $n + 1$ when the probe was presented. Indeed, a number of studies have shown that presentation of text for 50–60ms is sufficient for a reader to process the fixated word and show normal word frequency effects, even though the reader is fixating a blank space after the display change (e.g., Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner et al., 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003). Although 50–60 ms visibility may suffice to extract sufficient visual detail for the recognition of a fixated word, it should be noted that it may take more time to identify the word. ERP recordings in Sereno, Rayner, and Posner's (1998) influential study indicate that lexical selection begins approximately 100 ms after fixation onset and may extent up to 200 ms, and in their model attention shifting takes place approximately 150 ms after fixation onset. Therefore, we are inclined to conclude that the probe RT observed in Experiment 1 reflects primarily the attention deployment after the eyes landed at a new position.

However, longer RTs for the L2 and L3 locations could also be due to inhibitory attentional processes. Exogenous shifts to a previously attended location are subject to inhibition of return, IOR (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985; Rayner, Juhasz, Ashby, & Clifton, 2003; Weger & Inhoff, 2006), and inhibitory effects have been obtained for spatial locations that were selected with endogenous shifts (Weger, Abrams, Law, & Pratt, 2008). Since L2 and L3 probes were likely to occupy the location of previously attended text, the shifting of attention to these locations could have been inhibited. The L1 location could be exempted from IOR because the build-up of IOR takes time. We conducted two additional experiments that manipulated the visibility of text to gain more insight into the nature of attention allocation.

Experiment 2

Experiment 2 extended the testing of the attention shift hypothesis by changing the timeline between the offset of a visible sentence and the onset of the first fixation after the eyes crossed the invisible boundary. Specifically, all experimental sentences remained visible for another 150 ms after the eyes crossed the boundary. After this delay, the visual probe was presented on a subset of experimental trials. In prominent attention-shift models of eye movement control during reading, in particular the family of E-Z Reader models (Reichle et al., 1998; Reichle et al., 2003; Reichle, Pollatsek, & Rayner, 2006), saccade programming and attention shifting are closely coordinated. The programming of a saccade to an upcoming word ensues upon a partial processing of a fixated (attended) word, and it precedes a corresponding spatial shift of attention that ensues upon the recognition of the fixated word (in other models, for instance, SWIFT [Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012], the link between saccade programming and attention shifting is less deterministic. Nevertheless, word-specific processing outcomes control the shifting of attention from one word to the next)[2]. In view of these models' assumptions, the processing of a fixated word for approximately 150 ms was expected to increase the right visual field advantage. That is, the full recognition of the fixated word should be relatively common during the 150 ms viewing period (Sereno et al., 1998), and this should engender a shift of attention to the upcoming word to its right.

Method

Participants. Forty-two participants (28 females, with a mean age of 21) from universities around the Institute of Psychology,

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[2] It should be noted that these models are developed based on alphabetic languages and that some of their assumptions may need to be revised for Chinese text (Li, Rayner, & Cave, 2009; Zang, 2019).

Chinese Academy of Sciences took part in the experiment. They were from the same participant pool as that in Experiment 1 but had not participated in the previous experiment.

Apparatus. The same setup was used as in Experiment 1.

Materials and procedure. The design was the same as that of Experiment 1 except that the sentences remained visible for 150 ms after the eyes landed to the right of the boundary. On a subset of trials, the disappearance of a sentence was immediately followed by the presentation of a probe at one of seven probe locations. When the duration of the fixation after the boundary crossing was shorter than 150 ms, the sentence would not disappear, and participants could read the whole sentence (about 2% of trials). Probe RTs on these trials were not included in the analyses.

As in Experiment 1, the actual presentation of probes was slower than intended due to the time needed to detect a fixation, computation of the implementation, and the screen refresh rate. Post hoc analyses showed that average latency between boundary crossing and fixation onset was 15.35 ms (*SD* = 8.12 ms, min = 1 ms, max = 54 ms). The average latency between fixation onset and probe display was 203.12 ms (*SD* = 8.93 ms, min = 182 ms, and max = 239 ms).

Data Selection and Data Analysis

The selection of data and their analyses were similar as that of Experiment 1. Again, trials were removed when they yielded extremely longer RT outliers (>3000 ms, 0.1%), incorrect target present/absent choices (3.5% trials). We also removed trials with a blink during the boundary crossing saccade (0.8%), trials in which the eyes crossed the boundary due to a drifting of the eyes during a fixation (5.8% trials), and trials on which the probe was presented 300 ms or more after the eyes crossed the boundary (0.3%)[3]. In total, 9,998 trials were left after the removal of these trials. Again, the distribution of RTs was positive, and log-transformed values were analyzed. The skewness of model residuals improved substantially, from 0.95 to 0.49, when a small number of trials with outlier residuals (*n* = 116, 0.8%) was removed.

Results

The mean accuracy of comprehension questions was 96%. Mean detection RTs and their standard errors are shown as a function of probe location in Figure 3. Overall, the effect pattern was quite similar to the results of Experiment 1: The mean RT for foveal probes and the mean RT for the other locations, 716 ms and 724 ms, respectively, did not differ significantly ($b = -0.003$, $SE = 0.006$, $t = -0.442$, $p = .659$), whereas right visual field probes were responded to faster, 719 ms, than probes presented in the left visual field, 730 ms ($b = -0.017$, $SE = 0.005$, $t = -3.568$, $p < .001$). The main effect of probe's eccentricity was now reliable. RTs increased from 715 ms, to 725 ms, to 733 ms, for the 1-, 2-, and 3-character location, respectively ($b = 0.014$, $SE = 0.006$, $t = 2.455$, $p = .014$). Different from Experiment 1, the interaction of visual field and eccentricity effects was marginally significant ($b = -0.014$, $SE = 0.007$, $t = -1.962$, $p = .057$). The interaction reflects the fact that RTs varied less as a function of location when probes appeared to the right of fixation than they appeared to the left. The interaction between quadratic trend and visual field was also close to significant ($b = -0.019$, $SE = 0.010$, $t = -1.909$, $p = .056$). The quadratic trend of eccentricity was not significant ($b = -0.005$, $SE = 0.010$, $t = -544$, $p = .586$).

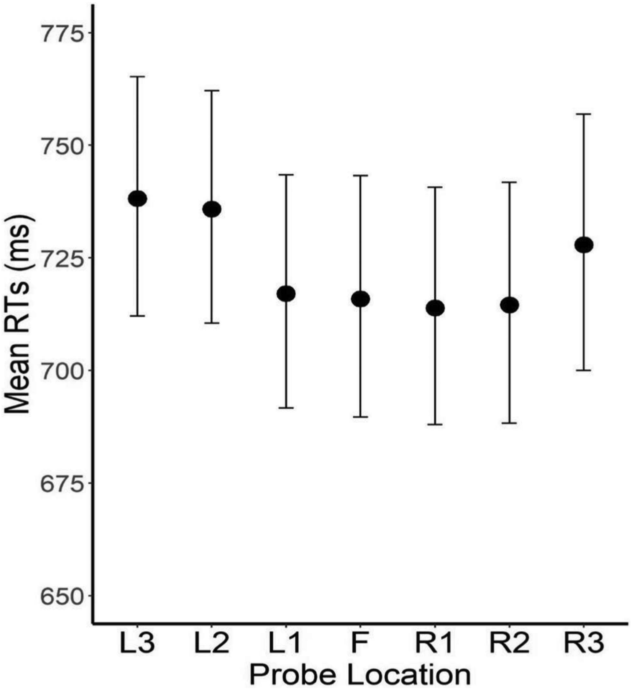

Figure 3. The mean RTs for each display condition in Experiment 2. The error bars indicate standard errors.

Post hoc Dunnett comparisons, as implemented in the *glht* function of R library *multcomp*, were applied to the pruned model to determine whether there was a stronger spatial bias toward the right in Experiment 2. Since the differences between the foveal and the L2 and L3 locations were reliable in Experiment 1, more frequent shifts of attention from the fixated location to the upcoming word in Experiment 2 were expected to yield a somewhat stronger right visual field bias. Comparisons of the foveal location with the remaining six spatial locations showed, however, that this was not the case. Only the differences between the foveal location and the L2 location ($z = 2.359$, $p = .087$), and between the foveal location and the L3 location ($z = 2.506$, $p = .060$) were marginally significant. No other difference approached significance (all *p* values > .66).

Discussion

The change in the time line between the offset of an experimental sentence and the onset of the first postboundary fixation had no striking effect on probe detection. As in Experiment 1, the visual field influenced RTs, with a faster detection of probes in the right visual field, as should occur if shifts of attention progressed from the fixated word to the next word in the text. In Experiment 2, RTs to probes also increased with eccentricity. As with Experiment 1,

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[3] We used identical data exclusion methods in all of the three experiments. However, in Experiment 1, we did not find any trial on which the probe was presented 300 ms or more after the eyes crossed the boundary.

the right visual field advantage can be accounted for by spatial shifts of attention toward upcoming words that facilitated processing at the attended location or by IOR that impeded the detection of probes at a previously attended L2 or L3 location.

According to both the attention-shift and the IOR hypotheses, attention allocation should have been shifted farther toward the right in Experiment 2 than that in Experiment 1. That is, more time was available for the shifting of attention in that direction, and the linguistic processing of a fixated word should have propelled attention toward the right. Visual field differences were, however, numerically smaller—rather than larger—in Experiment 2, and paired contrasts suggested that the bias toward the right was diminished rather than augmented. To determine the robustness of the decrease of the visual field effect, we conducted a supplementary analysis that included three fixed factors: visual field (left vs. right), experiment (1 vs. 2), and their interaction. The two main effects were reliable, with shorter RTs for the right visual field ($b = -0.062$, $SE = 0.018$, $t = -3.397$, $p < .001$) and longer RTs for Experiment 2 ($b = 0.042$, $SE = 0.004$, $t = 10.324$, $p < .001$), but the visual field by experiment interaction did not even approach significance, $t = .347$, $p = .729$.

While this statistical comparison suggests that the attention shifting toward the right was not weaker in Experiments 2 than that in Experiment 1, the reversal of the expected effect, that is, numerically smaller rather than larger right visual field benefits in Experiment 2, is difficult to reconcile with extant theoretical conceptions in which the recognition of a fixated word propels a shift of attention to the next word in the text. Instead, the finding raises the possibility that the "immediacy assumption" (Just & Carpenter, 1980), according to which a processing outcome will immediately influence eye movement programming, does not apply to the spatial shifting of attention. Experiment 3 examined this possibility.

Experiment 3

Experiment 3 examined the link between processing outcomes and the direction of shifts of attention. During reading, there is generally little or no uncertainty regarding the location(s) from which new information is to be extracted. As a result, the specification of the attention shifting direction could be preset and assume a script-specific default value, which is left-to-right for Chinese text.

To determine whether the setting of attention shift direction is preprogrammed, the visible order of words was changed in Experiment 3 so that it progressed in a reversed direction, from right to left. All other aspects of the experiment were the same as in Experiment 2. If the direction of attention shifting was determined by immediate processing outcomes, that is, by the visible order of to-be-recognized words, then the visual field advantage should be reversed in Experiment 3, with faster probe detection RTs for left than for right visual field presentations. The reversal of reading direction should also influence the effect of IOR, as the reversal of reading direction should now inhibit the detection of probes at previously viewed word locations which are now to the right of fixation.

If, however, the immediacy assumption does not apply with regard to attention shift direction, that is, if the direction of an ensuing shift is routinely preprogrammed rather than being determined by a particular processing outcome, then attention should be shifted in the familiar left-to-right direction in Experiment 3, and right visual field probes could be detected faster than left visual field probes, irrespective of reading direction.

Method

Forty-two individuals (an average age of 22; 18 females) participated in the experiment. None of them had taken part in Experiments 1 or 2. The design and the materials were the same as in Experiment 2. The key difference between the two experiments was that the characters of the identical sentences were now ordered from the right margin toward the left, which is opposite to the legal reading direction for mainland (simplified) Chinese script. Readers were told that the reading direction was opposite to normal reading, and they need to read from right to left for comprehension. There were 20 practice trials before the formal experiment, and participants could read sentences well in spite of the unusual reading direction.

As in Experiment 2, there was some probe implementation delay, and post hoc analyses showed that average latency between boundary crossing and fixation onset was 12.09 ms ($SD = 7.60$ ms, min = 1 ms, max = 241 ms). The average latency between fixation onset and probe display was 206.89 ms ($SD = 8.75$ ms, min = 191ms, and max = 252 ms).

Data Selection and Data Analysis

Again, trials were removed when no probe was presented (~ 1.8%), when RTs were exceedingly long (>3,000ms, 0. 2%), when the incorrect button was pressed (1.9%), when a blink occurred during the boundary crossing saccade (2.9%), when the boundary was crossed due to eye drift (7.6% trials), and when the probe was presented 300 ms or more after the eyes had crossed the boundary (0.6%). The log transformed RTs of the remaining 10,269 trials were analyzed. Removal of a small number of trials with outlier residuals ($n = 69$, 0.6%) yielded a close-to-normal distribution of residuals (the skewness of the distribution of residuals improved from 1.14 to .60 for the maximal model). We report the coefficients of the pruned model.

Results

The mean accuracy of comprehension questions was once more very high, 97%, indicating that the change in reading direction did not impede sentence comprehension. The mean RTs for the seven probe locations and the corresponding standard errors are shown in Figure 4. As can be seen, the change in reading direction focused attention more strongly into the foveal location, and the mean RT for the foveal location was significantly shorter than the mean RT of the remaining locations, 679 ms and 692 ms, respectively ($b = -0.016$, $SE = 0.006$, $t = -2.976$, $p = .003$). Importantly, the change in reading direction did not yield the expected left visual field advantage. To the contrary, RTs were significantly shorter for right than for left visual field probes, 687 ms and 696 ms, respectively ($b = -0.015$, $SE = 0.004$, $t = -3.687$, $p < .001$). There was a linear trend for eccentricity, with RTs of 686 ms, 691 ms, and 698 ms for character positions 1, 2, and 3, respectively ($b = 0.020$, $SE = 0.005$, $t = 3.950$, $p < .001$). None of the other effects approached significance ($t < 1.0$).

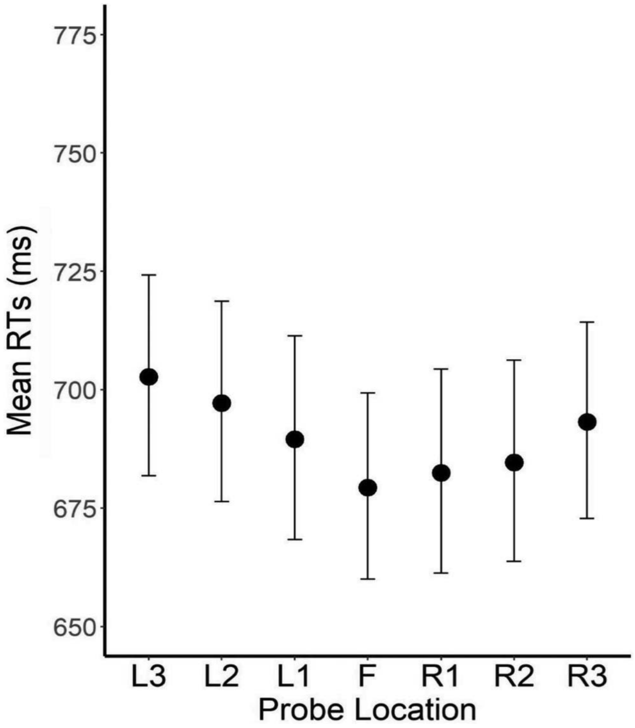

Figure 4. The mean RTs for each display condition in Experiment 3. The error bars indicate standard errors.

Post hoc Dunnett comparisons showed that the differences between the foveal location and the L2 location ($z = 3.539$, $p = .002$) and between the foveal location and the L3 location ($z = 4.721$, $p < .001$) were reliable. There was also a trend that RTs were shorter for the probes presented on the fovea than for those on the R3 location ($z = 2.530$, $p = .055$). No other differences approached significance (all p values $> .31$).

Discussion

The main results of Experiment 3 are straightforward: Probes were detected faster when they appeared in the right rather than the left visual field, and this occurred even though reading direction progressed in the opposite direction. This finding disagrees with a theoretical conception according to which a local processing outcome, the recognition of a fixated word, initiates the spatial shifting of attention to the location of an upcoming words to facilitate its processing. Had this been the case, probes in the left visual field advantage should have been detected more effectively than probes in the right visual field. The results of Experiment 3 also provide compelling evidence against an IOR account. Had IOR determined probe detection, RTs should have been longer—rather than shorter—when probes were presented at the location of previously attended text, that is, in the right visual field. Rather than being determined by an immediate processing outcome, the results of Experiment 3 indicate that the direction of attention shifting is preprogrammed during the reading of Chinese text.

General Discussion

The current study sought to determine whether spatial shifts of attention can account for the asymmetric spatial extension of the perceptual span toward to-be-read words during reading. The experimental approach sought to distinguish effects of attention shifting from effects of linguistic processing via the saccade-contingent replacement of a sentence with a to-be-detected visual probe on a subset of experimental trials. In Experiments 1 and 2, reading proceeded in a standard left-to-right direction, and text offset and probe onset occurred either immediately after the eyes landed to the right of a predefined boundary or after a delay of approximately 150 ms. In Experiment 3, Chinese characters were ordered in a reversed direction, from right to left, and text offset and the probe onset were delayed by approximately 150 ms after the eyes landed to the right of the boundary. All three experiments revealed robust effects of visual field, with shorter RTs when probes were presented to the right rather than to the left of fixation. All experiments showed increased RTs with increased eccentricities, and this trend was significant in Experiments 2 and 3.

The findings of Experiments 1 and 2 differ from the results of Fischer's (1999) study, where a similar probe detection task during left-to-right reading (with English text) did not yield location-specific probe detection effects. Moreover, the two studies yielded different effects for immediate and delayed probes. In Fischer's (1999) study, RTs were shorter when probe onset was delayed relative to the onset of a fixation; in the current study, by contrast, RTs were longer when probe onset was delayed (Experiment 2) than when it occurred immediately after the onset of the postboundary fixation (Experiment 1). The main procedural difference between the two investigations was the visibility of to-be-read text when the probe was presented. In our experiment, only the probe was visible. It is plausible to assume that the absence of competition between visible text and the probe increased the sensitivity of the probe task.

The current experiments also differ from Fischer's earlier work (1999) in that different script types were used. Fischer used alphabetic (English) script that concatenates letters to words of various lengths and separates words with visually distinct blank spaces. Chinese script, by contrast, uses visually distinct rectangular morpho-syllabic characters of equal length that can be concatenated to form multisyllabic words which are not separated by visually distinct interword spaces. It thus cannot be ruled out that the distinctiveness of character or word boundaries modulates attention shifts and that the strong marking of word boundaries in English abolishes or weakens directional shifts of attention.

Other considerations suggest, however, that the use of different script type may not account for the attention shift effects in Experiments 1 and 2. Both modern (simplified) Chinese and English are written from left to right, and they are read with an asymmetric extension of the perceptual span toward the right. The asymmetry is not diminished when English text is read. The span extended four letters to the left of fixation—or to the beginning of a fixated word—and up to 16 letters to its right—to the end of the fixated word and approximately two words to its right—in some of Rayner's seminal experiments (see, Rayner, 1998, 2009, for reviews). Estimates of the spatial extent of the span for Chinese text show a proportionally smaller spatial asymmetry, although the asymmetry appears to be equivalent for the two scripts when information density is taken into account (Feng, 2006). Based on these considerations, we are inclined to conclude that attention is shifted in a script-conform direction when reading English or Chinese and that differences in the experimental approach—rather than the differences between script types—account for the presence of robust visual field effects in Experiments 1 and 2 and for their absence in Fischer's (1999) study.

The effects of probe location in Experiments 1 and 2 are thus in general agreement with the view that asymmetries in the perceptual span during reading are linked to shifts of attention that progress with word order. The setting of attention shift direction could be established before a corresponding saccade is executed and facilitate the detection of a probe when it is presented near fixation or to the right of it (up to location R3 in Experiments 1 and 2). IOR could also account for the right visual field advantage in Experiments 1 and 2, as it would inhibit a return of attention to previously attended text.

However, neither process-contingent shifts of attention that progress with word order nor the build-up of IOR can account for the probe location effects in Experiment 3. According to these accounts, a reversal of reading direction should have resulted in a corresponding reversal of visual field effects; that is, RTs to probes should have been shorter when they were presented in the left visual field. Instead, RTs to probes were significantly shorter when they were presented in the right visual field. This implies that the allocation of attention during reading fixations was controlled neither by the IOR-like inhibition of previously fixated locations nor by the order of to-be-identified words. Instead, the setting of attention shift direction appears to be preprogrammed, presumably a consequence of years of consistent left-to-right reading of Chinese text.

Our results cannot be explained by the usefulness of visible linguistic information, which has been used to account for asymmetries in the perceptual span. According to this hypothesis, effective viewing windows are asymmetric because the masking of previously fixated (and already identified and thus less informative) words is less detrimental to the reading performance than the masking of to-be-identified upcoming (and thus more informative) words. Evidently, the main result of Experiment 3, that RTs to the probes were shorter when they were presented to the right rather than to the left of fixation, is not consist with this hypothesis.

Benefits reaped from the preprogramming of attention shift direction could be substantial. An inspection of reading times for sentences revealed considerably shorter durations when reading direction and ingrained attention shift direction matched (Experiment 2: 2,109 ms) than when they mismatched (Experiment 3: 3,682 ms). Saccade lengths were also longer when reading from left to right (Experiment 2: 2.55 characters) than reading from right to left (Experiment 3: 1.79 characters). High levels of reading fluency may require that attention shift direction is preset rather than being determined by processing outcomes during individual fixations, as the execution of outcome-contingent shifts of attention appears to be relatively time consuming (e.g., Hickey, van Zoest, & Theeuwes, 2010). Since the perceptual span of bilingual Hebrew-English and Arab-English readers is script-specific, automatic shifts of attention could be instantiated through the recognition of script-specific orthographic forms. Potential links between linguistic processing outcomes and attention shifting could be examined in future work.

Conclusion

In our study, we measured attention allocation during Chinese reading and found that more attention was deployed in the right than in the left visual field. This is consistent with the finding that the perceptual span is asymmetry toward the reading direction. Shift direction is not set during individual reading directions, however. Instead, shift direction appears to be set automatically for a particular writing system, and this default setting is difficult to change.

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(*Appendix follows*)

Appendix

Supplementary Analysis

Some may argue that given natural variability in word length, it would be helpful to know if there were any differences between left and right probes in within- vs. between-word locations from the fixated position. Readers typically fixate on the first character of a multi-character word (e.g., Zang, Liang, Bai, Yan, & Liversedge, 2013), and so it's possible that probes to the left of fixation occurred within a different word more often than probes to the right of fixation. In Experiments 1 and 2, probes to the left of fixation occurred within different words more often than probes to the right of fixation, while the situation was inversed in Experiment 3, in which probes to the right of fixation occurred within different words more often than probes to the left of fixation. However, in all of the three experiments, the largest difference happened between the L1 and R1 conditions (about 12%). The difference between the L2 and R2 conditions was about 3%, and the difference between the L3 and R3 conditions was less than 1% (see Table A3 for details). If this was the reason that caused the differences in probe RTs, we would have expected greater difference between the L1 and R1 conditions and less or no difference between the L2 and R2 condition and between L3 and R3 conditions. However, this was not the case. Indeed, Probe RTs are similar for L1 and R1 conditions. Thus, we argued that the differences in probe RTs should not be caused by the differences in whether fixation and probe were at different or same words.

Table A1

Coefficients of the Model When Fixation-to-Probe Delay (fix2probe) Was Added as a Predictor to Statistical Models

Contrast	*b*	*SE*	*t*	*p*
		Experiment 1		
(Intercept)	6.543	0.034	192.385	<.001
Foveal	−0.012	0.007	−1.634	.110
Visual field	−0.024	0.006	−4.404	<.001
Eccentricity	0.005	0.007	0.681	.499
Visual Field × Eccentricity	−0.001	0.007	−0.189	.851
Quadratic trend	−0.011	0.011	−0.976	.335
Visual Field × Quadratic	−0.007	0.010	−0.711	.477
fix2probe	0.000	0.000	−1.647	.100
		Experiment 2		
(Intercept)	6.452	0.067	96.444	<.001
Foveal	−0.003	0.006	−0.540	.589
Visual field	−0.018	.005	−3.534	<.001
Eccentricity	0.015	0.007	2.232	.031
Visual Field × Eccentricity	−0.015	0.007	−2.050	.047
Quadratic trend	−0.006	0.010	−0.559	.579
Visual Field × Quadratic	−0.020	0.010	−2.016	.044
fix2probe	0.001	0.000	2.063	.039
		Experiment 3		
(Intercept)	6.471	0.055	117.008	<.001
Foveal	−0.016	0.005	−2.966	.003
Visual field	−0.016	0.007	−2.438	.019
Eccentricity	0.020	0.006	3.162	.003
Visual Field × Eccentricity	−0.001	0.006	−0.166	.869
Quadratic trend	−0.002	0.009	−0.231	.817
Visual Field × Quadratic	−0.002	0.009	−0.269	.789
fix2probe	0.000	0.000	1.083	.279

(*Appendix continues*)

Table A2
The Results of Post-Hoc Dunnett Comparisons, as Implemented in the Glht Function

Contrast	*b*	*SE*	*z*	*p*
		Experiment 1		
L1-F0	0.018	0.010	1.888	.233
L2-F0	0.030	0.009	3.231	.007
L3-F0	0.024	0.010	2.511	.057
R1-F0	−0.002	0.010	−0.233	1.000
R2-F0	0.001	0.009	0.123	1.000
R3-F0	0.001	0.010	0.115	1.000
		Experiment 2		
L1-F0	−0.007	0.009	−0.809	.930
L2-F0	0.021	0.008	2.510	.060
L3-F0	0.023	0.009	2.606	.047
R1-F0	−0.003	0.009	−0.348	.999
R2-F0	−0.010	0.008	−1.228	.685
R3-F0	−0.003	0.009	−0.350	.999
		Experiment 3		
L1-F0	0.013	0.008	1.610	.424
L2-F0	0.026	0.008	3.368	.004
L3-F0	0.034	0.008	4.253	<.001
R1-F0	−0.001	0.008	−0.145	1.000
R2-F0	0.008	0.008	1.083	.799
R3-F0	0.018	0.008	2.242	.121

Table A3
Proportions of Trials in Which Probe and Fixation Were at Different Words

Experiment	L1	L2	L3	R1	R2	R3
Experiment 1	0.649	0.970	0.991	0.524	0.943	0.990
Experiment 2	0.666	0.974	0.996	0.508	0.940	0.982
Experiment 3	0.493	0.967	0.983	0.633	0.956	0.983

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