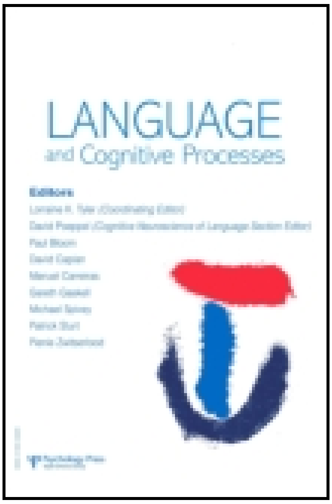

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Acquisition of linguistic information to the left of fixation during the reading of Chinese text

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Acquisition of linguistic information to the left of fixation during the reading of Chinese text

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The linguistic properties of the first (critical) character of a two-character Chinese word were manipulated when the eyes moved to the right of the critical character during reading to determine whether character processing is strictly unidirectional. In Experiment 1, the critical character was replaced with a congruent or incongruent character or left unchanged. Critical character changes did not influence the fixation duration, but incongruent changes led to

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more regressions than congruent changes. In Experiment 2, the critical character was replaced with either a homophonic or a non-homophonic character when it was to the left of fixation. The fixation following the change was now longer when the replaced character and the critical character were homophones than when they were phonologically dissimilar. These results indicate that readers obtain phonological and semantic information to the left of a fixated character and that the recognition of consecutive Chinese characters is not strictly unidirectional.

Readers obtain useful linguistic information preferentially to the right of the centre of vision during individual reading fixations. Studies that used eye-movement contingent display changes (McConkie & Rayner, 1975; Rayner, 1975) to control the visibility of text revealed that readers typically obtain useful linguistic information from the fixated word and graphemic and phonological information from the next (parafoveal) word in the text when it is a spatially distinct unit (Pollatsek, Lesch, Morris, & Rayner, 1992). This information is used when the parafoveally previewed word is subsequently fixated, yielding a parafoveal preview benefit (see Rayner, 1998, for a comprehensive review). The asymmetric extension of linguistic information acquisition toward the right is a function of word order. It is reversed when right-to-left ordered Hebrew text is read (Pollatsek, Bolozky, Well, & Rayner, 1981) or when the spatial ordering of English text is reversed so that it is written and read from right-to-left (Inhoff, Pollatsek, Posner, & Rayner, 1989).

A corresponding right-directed spatial processing bias occurs during the reading of non-alphabetic left-to-right ordered Chinese text. Skilled readers of Chinese typically obtain useful information up to 2–3 characters to the right of fixated character and from one or two characters to its left (Chen & Tang, 1998; Inhoff & Liu, 1997, 1998). Similar to readers of alphabetic scripts, they also integrate graphemic and phonological character information across successive right-directed fixations (Liu, Inhoff, Ye, & Wu, 2002; Tsai, Lee, Tzeng, Hung, & Yen, 2004). The reading of spatially distinct morpho-syllabic Chinese characters thus appears to be similar to the reading of words in alphabetic scripts. Two influential theoretical conceptions offer accounts for the effect of word order on the spatial asymmetry of information acquisition during reading fixations. According to one view, linguistic processing of text involves the selection of non-overlapping spatial segments of text and the processing is strictly unidirectional, progressing from one segment of text to the next. In one such class of models, sequential attention shift (SAS) models, attention is focused at one linguistic unit at a time, and recognition of an attended unit initiates the programming of a saccade, a shift of attention to the next unit. The linguistic processing of consecutive units in the text is thus non-overlapping, and it progresses unidirectionally from one unit to the next (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; Salvucci, 2001) which will result in right-directed processing bias for new text. Alternatively, the linguistic processing of consecutive linguistic units may not be strictly unidirectional, and adjacent segments of text may be processed during more than one fixation. During each fixation, readers may seek information from the previously attended (and processed) text to the left of fixation, from the fixated linguistic unit, and from text to the right of fixation. A gradient of processing may give preference to to-be-identified processing segments, thereby biasing information acquisition toward the right for the left-to-right ordered text (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Reilly & Radach, 2003, 2006).

A key difference between the two conceptions is the use of information from which the eyes move away, i.e., information that is visible to the left of fixation during left-to-right sentence reading. If the processing of consecutive spatially defined linguistic units was strictly unidirectional (so that the recognition of one linguistic unit must be completed before the processing of the next unit can begin), then readers should not obtain any useful *linguistic* information from the unit to the left of fixation.

One critical study has used Chinese text to examine the unidirectional processing hypothesis. Specifically, Inhoff and Wu (2005) sought to determine whether the parsing of Chinese characters into words progresses strictly from one identified character to the next, which we refer to as the *unidirectional character processing assumption*. In the study, participants were asked to read two types of Chinese sentences each of which contained a critical four-character sequence, Cr1234. In unambiguous sentences, this character sequence was composed of two consecutive two-character words, Wd12 and Wd34. In ambiguous sentences, the sequence was also composed of two consecutive two-character words, Wd12 and Wd34, but characters 2 and 3 also formed a legal word on their own (that was typically contextually inappropriate). Even though the lexicality of Wd23 should have been 'hidden' if the parsing of characters into words was strictly unidirectional, readers spent more time viewing the Cr1234 and the Cr34 character sequences in the ambiguous condition.

A viable alternative account, that reconciles these results with a strictly unidirectional character processing conception, cannot be ruled out, however. Character recognition could have been strictly unidirectional, progressing from one character to the next, but the grouping of characters into words may have been tentative and subject to revision when additional information was obtained. In the ambiguous condition, readers could have grouped characters 1 and 2 into a word (Wd12) and then abandoned this assignment in favour of a Wd23 grouping when the next character was recognised. This grouping was subsequently revised in favour of Wd12 and

Wd34 when the fourth character of the sequence was recognised. Revisions in the grouping of characters into words can thus plausibly account for the increase of viewing time in the ambiguous parsing condition.

Several studies with English text sought to test the unidirectional processing hypothesis. In English and most other alphabetic writing systems, words are spatially marked *linguistic* units, and it is the processing of words that is assumed to be strictly unidirectional according to SAS models.

Binder, Pollatsek, and Rayner's (1999) study is particularly relevant for the current study. A boundary paradigm (Rayner, 1975) was used to manipulate the visibility of a single (target) word in the sentence so that it could be changed when the eyes moved to the next word in the sentence, i.e., when it was to the left of fixation. Three left-of-fixation post-view conditions were created so that the target replacement word was either a contextually consistent word, an inconsistent word, or the target itself (in a baseline condition). When target changes resulted in a left-directed re-inspection of the target area, a second display change was implemented during the left-directed saccade to restore the original target. Consistent with the unidirectional processing hypothesis, semantic information to the left of fixation had no effect on reading when the eyes continued to move to the right after the target was replaced with a contextually congruent or incongruent word. When, however, readers re-inspected the target area, less time was spent re-inspecting the target in the congruent than the incongruent change condition. Therefore, target re-reading durations indicated that semantic information had been obtained from the temporarily visible replacement word to the left of fixation.

To reconcile this finding with the strictly unidirectional processing assumption, Binder et al. (1999) proposed that fixation location and processing location diverged on those trials in which the target area was re-inspected. According to one such account, readers erroneously overshot the to-be-fixated target so that the location of a fixation was accidentally ahead of the actual processing location; according to another account, readers moved their eyes prematurely off a fixated target, i.e., before it had been identified. In both cases, readers programmed a regression to the attended target location from which congruent or incongruent semantic information had been obtained.

Other findings pose, however, additional difficulties for the unidirectional processing hypothesis. Similar to Binder et al. (1999), Starr and Inhoff (2004) placed an invisible boundary immediately after a critical word. A saccade to the right of boundary replaced the critical word with a length-matched sequence of visually dissimilar (and orthographically illegal) letters. This manipulation increased the time spent viewing the following word relative to a baseline condition in which the critical word was left unchanged. On one hand, this finding challenges the unidirectional processing hypothesis; on the other hand, it could have been the visual change to the left of fixation per se, rather than the withholding of useful linguistic information, which increased target viewing durations (Pollatsek, Reichle, & Rayner, 2006). The available empirical evidence must thus be considered equivocal.

The current study extends prior testing of the unidirectional processing hypothesis by using an experimental approach that combined the strengths of earlier work. We used the power of eye-movement-contingent changes of text to the left of fixation (Binder et al., 1999; Starr & Inhoff, 2004) to manipulate linguistic properties of a Chinese character when it was visible to the left of fixation. We used Chinese text however, and we manipulated the visibility of a single character, rather than a word, when it was to the left of fixation. As noted before, Chinese characters are visually distinct linguistic units and most of them can be words on their own. Robust effects of character frequency in addition to robust effects of word frequency (Peng, Liu, & Wang, 1999; Yan, Tian, Bai, & Rayner, 2006) show that character units make a distinct lexical contribution to visual word recognition in Chinese. The selection for linguistic processing may, therefore, comprise a single character, rather than a word, when Chinese text is read, and recognition could progress unidirectionally from one character to the next.

The current study tested the unidirectional character processing assumption by manipulating the visibility of the first character of a two-character word when the eyes moved to the right of it. The changed character was part of a word in order to create a particularly stringent test of the unidirectional character processing assumption, based on the assumption that lexical coherence should increase the opportunity for the extraction of linguistic information to the left of fixation. The changed character will be part of the fixated word when the eyes land on the word's second character, and it will be part of the word that is immediate to the left of fixation when the eyes land on the following character. If, under these conditions, readers sought linguistic information from the character to the left of fixation, then a change of its linguistic content should influence fixation durations. If visually distinct Chinese characters were recognised individually, however, progressing strictly from left to right, then changing a (previously recognised) character to the left of fixation should not influence fixation duration – even when the change occurred within a fixated word.

EXPERIMENT 1

Similar to Binder et al. (1999), Experiment 1 used a boundary paradigm to manipulate the meaning of a visually distinct linguistic unit when the eyes moved to the right of it during left-to-right sentence reading. Three conditions were created: one in which the unit, a Chinese target character was left unchanged (baseline); one in which it was replaced with a different but contextually congruent character; and one in which it was replaced with a matched contextually incongruent character. If Chinese character processing was strictly serial, then a change of target character meaning should not influence the duration of the following fixation.

Method

Participants. Twenty-four students at the National Yang-Ming University were paid to participate in this experiment. All of them are native speakers of Chinese with normal or corrected vision.

Materials. Ninety declarative sentences were formed for the experiment, each of which contained a two-character target word. All sentences were written in traditional Chinese script, the official script of Taiwan, Hong Kong, and a commonly used script of native Chinese speakers outside of mainland China. All characters were ordered from left to right; punctuation marks (if any) were at least two characters to the right and the left of the target words. None of the sentences contained left-to-right parsing ambiguities or sentence segments that would have created comprehension difficulties. Target words were selected so that they contained two complex constituent characters, each of which contained a semantic and phonetic radical. The first (critical) character of all target words could be replaced with a visually equally complex character with a congruent or incongruent character meaning. A sample sentence with replacement characters is shown in Figure 1.

The effectiveness of the semantic congruence manipulation was examined in a separate norming study in which the original sentences were presented with either the critical (unchanged) character, the congruent character, or the incongruent character. Twelve native Chinese-speaking students from National Yang-Ming University (who did not participate in the reading experiment) were asked to rate the original characters' and the two replacement characters' contextual congruence on a 7-point rating scale, with seven indicating very good and one indicating very poor congruence. The rating points are 6.84, 4.61, and 1.32 for the critical (original), congruent, and incongruent character condition, respectively, $F_2(2, 178) = 830.096$, $p < .01$. The key difference between the congruent and incongruent post-view condition was highly reliable, $t_2(89) = 20.897$, $p < .01$.

Care was taken to match the three types of left-of-fixation post-view characters on visual and linguistic properties. According to the Academia Sinica balanced corpus (1998), the average character frequencies of the critical, congruent, and incongruent character were 162.9, 371.5, and 253.2 per million, and the average number of strokes were 13.2, 12.7, and 12.3,

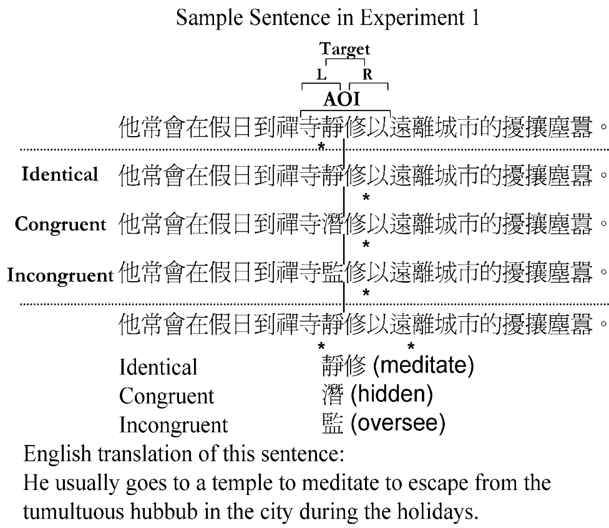

Figure 1. An illustration of a sentence in Experiment 1. Three events in the post-view (C2) conditions. The bar indicates the boundary location, and the asterisk represents eye position. The top line represents the last fixation before the boundary is crossed, and the second, third, and fourth lines represent the first fixation after the boundary is crossed under different conditions, the identical, congruent, and incongruent conditions respectively. The bottom line represents the first fixation after readers' eyes left to R-AOI location.

respectively. Neither difference approached significance among the three types of post-views, with character frequency, $F_2(2, 178) = 3.400$, $p > .06$, and with number of strokes, $F_2(2, 178) = 2.108$, $p > .12$.[1] The detailed account of character properties is shown in Table 1.

Apparatus. Eye movements were recorded from the right eye using an EYELINK I eye-tracking system manufactured by SR Research. The sampling rate was 250 Hz and the absolute spatial resolution was better than 1/2 character space. The sentences were displayed in black with a light-grey background on a ViewSonic PT795 monitor. The screen resolution was set to 800×600 pixels. With this resolution, each character was displayed within a 24×24 pixel matrix and the blank space in between spatially

[1] In Experiment 1, contextually congruent and incongruent critical (replacement) characters could form a word with the 2nd character in almost all cases (94% in the congruent and 91% in the incongruent condition). The word frequency of these words was 7.7, 9.5, and 3.3 per million in the identical, related, and unrelated conditions, respectively, and the difference between the congruent and incongruent condition was not significant, $t(89) = 1.532$, $p = .129$. Furthermore, the frequency of congruent and incongruent characters themselves was also similar in the two congruent and incongruent condition, $t(89) = 1.293$, $p = .199$.

TABLE 1
Visual and lexical properties of the critical character and of congruent and incorrect replacement characters in Experiment 1

	Character type		
	Identical	*Congruent*	*Incongruent*
Example	靜	潛	監
Translation	/jing4/	/qian2/	/jian/
Mean no. of strokes	13.2	12.7	12.3
Mean character freq.	162.9	371.5	253.2
Congruent rating	6.84	4.61	1.32

Note: Character frequency: 1 million characters.

adjacent characters was 4×24 pixels. The viewing distance was 70 cm, at which each character subtended 0.82°. In order to achieve a relatively rapid implementation of left-of-fixation character changes in the congruent and incongruent conditions, we used a set of VGA routines from a PCTSCOPE library (Tsai, 2001). These routines increased the vertical refresh rate of the display to 167 Hz and preloaded all images into VGA memory before each trial. The timing error of changing displays in the program was therefore less than 6 ms. Eye-contingent display changes were accomplished by combining the PCTSCOPE library for fast display changes with EYELINK software for eye position detection. The duration from acquiring the current eye position to the display of an eye-movement contingent image was less than 12 ms and virtually all critical character changes were implemented while the eyes moved to the right of it.

Procedure and design. Participants were tested individually. They were instructed to read individual sentences fluently for comprehension and told that sentence reading would be followed by a comprehension test on a considerable number of trials. After setting up the eye cameras, a horizontal three-point calibration was performed near the vertical midline of the screen. A circular marker appeared in random order near the left, centre, and right side of the monitor screen. Calibration was followed by a similar validation routine that checked the consistency with which the recorded eye position mapped onto corresponding screen locations. The calibration was considered successful when the measuring error was less than 1/5 character space. A new calibration was performed every 15 trials, and when there was some indication that the recorded fixation location had drifted off the actual fixation location.

Each trial started with a fixation marker presented in the location of the first character of the sentence. After participants fixated the marker, the experimenter pressed a button and the sentence appeared on the screen. Participants read it at their own pace and pressed a button when sentence reading was completed. After this, the sentence disappeared and the next fixation marker appeared. A comprehension test followed the reading of approximately every 3rd sentence. Participants were asked to decide whether the previously read sentence and the test sentence, which differed by only one word, expressed the same meaning. Virtually all choices (over 90%) were correct, indicating that readers successfully read individual sentences for meaning. Twelve practice trials preceded the reading of 90 experimental sentences to familiarise participants with the experimental procedure. There were short breaks after every 30 trials to prevent fatigue, and the experiment took approximately 35 min to complete.

An invisible boundary was placed between the first (critical) and second character of the target word to implement one of three experimental conditions during the reading of experimental conditions. The critical character was left unchanged when the eyes moved to the right of the boundary in a baseline condition, and it was replaced with either a contextually congruent or incongruent character in two experimental conditions. The character replacement occurred only when the saccade moved the eyes to the right of the critical character location onto the second character of the target word or the character immediately to its right (this is referred to as right-side area of interest [R-AOI] in the following). The critical (original) character was always visible when the eyes moved outside the R-AOI, irrespective of the direction of and size of the outgoing saccade (see Figure 1).

Participants were asked to ignore any disturbance that might occur while they were reading the experimental sentences as such changes were irrelevant to the perceived primary task, the successful answering of comprehension questions. In post-experiment interviews, participants were asked whether they noted visual changes during sentences and how frequently such disturbances occurred. A large proportion of participants did not notice any display changes, and those who did noticed only a relatively small proportion of the changes. Participants who noticed display changes with some regularity, 15 or more times, were excluded from the study.

Participants read 90 experimental sentences with only one of the conditions presented for each target. The three types of post-view were counterbalanced over participants. There were 30 trials in each condition.

Measurement and data selection. The strongest test of the unidirectional character processing assumption would require that effects of left-of-fixation character changes be measured when the second character of the two-character word was fixated. However, the frequency with which this character was fixated was relatively low, slightly less than 40%, due to forward-directed saccade size of approximately 2.5 character during Chinese reading (Inhoff & Liu, 1997, 1998). To increase the number of eligible trials, we extended the measurement area one character to the right. This doubled the number of trials that could be used to examine the effect of a left of fixation character change and can be justified on theoretical grounds – based on the assumption that a proportion of the saccades that were directed at the right side character of the target word landed on the next character due to oculomotor overshoot (McConkie, Kerr, Reddix, & Zola, 1988). This spatial extension was not without risk. The inclusion of fixations that landed immediately to the right of the target word could have diminished the effect of a critical character change which would have favoured the unidirectional processing hypothesis. Similar to the right side area of interest, R-AOI, the L-AOI consisted of two characters, the critical character and the character to its left. In addition, we examined the effect of critical character changes on the viewing of the combined L-AOI and R-AOI, referred to as general AOI.

The time spent viewing the R-AOI was of primary theoretical interest. According to the unidirectional processing hypothesis, the meaning of a replacement character should not have any effect on the time spent viewing this area – unless the critical character area is re-inspected. In view of Binder et al.'s (1999) results, re-inspection duration (but not re-inspection frequency) was expected to be longer in the incongruent than the congruent condition as some saccades to the right of the boundary were prematurely launched or due to saccadic overshoot. Independent of this, visual display changes in the two experimental conditions were expected to attract some re-inspections to the L-AOI. Consequently, re-inspections should be more common in the two experimental conditions than in the baseline condition.

As is customary in oculomotor reading research, several oculomotor indexes were computed to determine the effects of the experimental manipulation. General AOI and target viewing were examined using (1) the duration of the first fixation duration (FFD); (2) gaze duration (GD), consisting of the sum of all first-pass fixation durations until the eyes move outside the AOI; and (3) total viewing time, consisting of the cumulated time spent viewing the AOI area, including the time spent re-reading it. First fixation duration and the gaze duration were also computed for the R-AOI. Following Binder et al. (1999), we computed two separate left-side AOI measures, one comprising the frequency with which the eyes regressed back into this area after boundary crossing and one comprising the duration of second-pass fixation. This re-reading duration measure consisted of the ratio of all fixation durations on this area divided by the number of trials in that condition. Finally, we also computed spillover duration that consisted of the duration of the first fixation to the right of the R-AOI.

Participants who noticed display changes with some regularity, i.e., on 15 or more trials, were excluded. Individual trials were excluded when the first fixation duration on the general AOI was less than 100 ms or ± 2 standard deviations from a participant's mean value. Trials in which the eyes blinked, drifted just prior to moving into the R-AOI, or the display change occurred during a fixation rather than during a saccade were excluded. These criteria excluded 18% of the trials from analyses.

Results

General AOI. The means and standard errors first fixation duration, gaze duration, and total viewing duration measures for the general AOI are shown in Table 2 as a function of the left-of-fixation character display condition.

The critical character manipulation influenced neither first-fixation duration nor gaze duration, all $F < 1$. It had a profound effect on total viewing duration, however, with an main effect size of over 100 ms, $F_1(2, 46) = 6.207$, $p < .01$; $F_2(2, 178) = 8.720$, $p < .01$. Total viewing durations were relatively long in the incongruent condition and relatively short in the baseline condition. Critically, the 59 ms shorter total viewing duration in the congruent than the incongruent condition was reliable in a planned paired comparison, $t_1(23) = 2.383$, $p < .05$; $t_2(89) = 2.064$, $p < .05$.

Since total viewing duration includes the time spent re-reading the critical character area, the effect of semantic congruency during the reading of the four-character AOI area could be due to oculomotor targeting errors or due to premature saccades to the right of the boundary that were followed by corrective regressions toward or at the critical character location. If this was

TABLE 2

Eye movement measures for areas of interest (AOI, four-character area: the target word and one character immediately to the left and right of it) as a function of post-view type in Experiment 1. First fixations, gaze durations and total viewing durations are measured in ms. Standard errors of the mean are shown in parentheses.

	Post-view character type		
	Identical	*Congruent*	*Incongruent*
First fixation duration	258 (5)	261 (6)	257 (5)
Gaze duration	466 (20)	486 (27)	483 (27)
Total viewing duration	546 (26)	589 (41)	648 (50)

the case, then right-side AOI viewing should be relatively immune to effects of the left-side critical character manipulation.

R-AOI. The means and standard errors of the first fixation duration and gaze duration for this area are shown in Table 3. The duration of the first fixation in the right-side AOI was 8 ms longer in the congruent condition than the baseline condition and 5 ms shorter in the incongruent condition than the baseline condition. The main effect of the critical character manipulation was not reliable, however, all $F < 1$, and a paired contrast between the congruent and incongruent condition indicated that the 13 ms difference did not even approach significance, all $t < 1$.

Gaze duration showed a similar effect pattern. Relative to the baseline condition, gaze duration in the incongruent and congruent conditions were increased by 16 ms and 5 ms, respectively. The main effect of the left of fixation change was not reliable over participants, $F_1(2, 46) = 1.295$, $p > .25$, but did reach significance over items, $F_2(2, 178) = 3.286$, $p < .05$. The key 11 ms difference between the congruent and incongruent conditions once more did not even approach significance, all $t < 1$. Together these two sets of data indicate that the effects of a congruent and incongruent left-of-fixation character change did not significantly differ during first pass right side AOI reading.

To remove potential effects of saccadic overshoot, a supplementary analysis was conducted that excluded trials in which a fixation of the R-AOI was followed by a regression toward the changed character location. This virtually eliminated the effect of semantic congruity; neither first fixation duration nor its gaze duration was influenced by the contextual congruity manipulation, all $F < 1$. Furthermore, the duration of the first

TABLE 3

Eye movement measures for the R-AOI (the second character of the target and its next character) and L-AOI (the first character of the target and its left character) as a function of post-view type in Experiment 1. First fixations, gaze durations on R-AOI are measured in ms, second-pass time on L-AOI (in ms) and regression rate to L-AOI (in percentage values). Standard errors of the mean are shown in parentheses.

	Post-view character type		
	Identical	*Congruent*	*Incongruent*
First fixation duration	256 (8)	264 (9)	251 (6)
Gaze duration	273 (12)	289 (11)	278 (10)
Regression rate to L-AOI	4.0 (1.7)	4.8 (1.3)	8.6 (1.6)
Second-pass time on L-AOI	7.8 (3.4)	14.6 (4.0)	23.5 (4.7)

(spill over) fixation to the right of the R-AOI area was not influenced by the critical character manipulation, $F < 1$. The results of these supplementary data are shown in Table 4. Together, these findings demonstrate that readers do not use the meaning of a character to the left of fixation even when this character is either part of – or very close to – the fixated word.

L-AOI. Regressions into this area and second pass re-reading time (computed as in Binder et al., 1999) are also shown in Table 3. Regressions were numerically more common in the incongruent condition than in the other two conditions, $F_1(2, 46) = 4.870$, $p < .05$; $F_2(2, 178) = 1.775$, $p > .15$. Planned-comparison revealed a higher regression rate in the incongruent than the congruent condition, and the effect was reliable over participants, $t_1(23) = 2.370$, $p < .05$, though not over items, $t_2(89) = 0.836$, $p > .4$. Examination of the data showed a relatively large variability in the item data, as there were relatively few observations for some items. To decrease variability in the item data, a revised analysis included only those 65 items that received three or more regressions in each of the three experimental conditions. Although this reduced variability, it did not yield a reliable difference between the consistent and the inconsistent character conditions, $t_2(64) = 1.05$, $p > .25$.

Second-pass fixation durations were also influenced by the critical character manipulation, $F_1(2, 46) = 6.468$, $p < .01$; $F_2(2, 178) = 3.191$, $p < .05$. Planned-comparison revealed longer second-pass durations in the incongruent than the congruent condition, and this effect was marginally significant over participants, $t_1(23) = 1.967$, $p = .061$. It did not even approach significance over either the full set of items, $t_2(89) = 0.933$, $p > .35$, or the reduced set of items $t_2(64) = 1.24$, $p > .2$, however.

TABLE 4
Eye movement measures for the R-AOI as a function of post-view type in Experiment 1 (when removing following trials of re-reading on L-AOI). First fixations, gaze durations, spillover durations on R-AOI are measured in ms. Standard errors of the mean are shown in parentheses.

	Post-view character type		
Removing re-reading	*Identical*	*Congruent*	*Incongruent*
First fixation duration	253 (8)	259 (7)	253 (6)
Gaze duration	271 (11)	282 (9)	278 (12)
Spillover duration	263 (9)	264 (8)	262 (7)

Discussion

The main findings of Experiment 1 are in general agreement with the predictions of the unidirectional character processing assumption. The contextual congruence of a replacement character, that took the place of the critical character when the eyes moved to the right of it, did not influence the duration of the following fixation. This occurred even though the replaced character and the adjacent R-AOI character formed a lexical unit.[2] Changes in the meaning of the left-of-fixation character replacement also had no effect on the duration of the fixation that followed a right-directed saccade out of this area. These data are consistent with the unidirectional character processing assumption. The meaning of the critical character was extracted before the eyes moved to the right of it, and changes in character meaning that occurred after this were therefore ineffective.

The meaning of the left-of-fixation character influenced, however, the re-reading of the critical area of text. Specifically, more total viewing time was spent on the General AOI in the incongruent than the congruent condition. Furthermore, the L-AOI data indicate that the effect of critical character meaning was primarily due to the larger number of regressions into the L-AOI in the incongruent condition and to the ensuing longer re-reading time, although the two L-AOI effects were robust over participants only. The relatively large and highly robust semantic congruity effect in the total viewing durations for the four character general AOI was, therefore, not fully captured in the re-reading time of the two character L-AOI area, indicating that deleterious effects of semantic incongruity were not confined to L-AOI re-reading.

The numerical influence of critical character meaning on L-AOI reading does not reject the unidirectional character processing assumption. According to Binder et al. (1999) re-reading of the L-AOI was a likely consequence of saccadic overshoot or of premature saccades that moved the eyes to the right of the critical character before it had been identified. In either case, attention would have been to the left of fixation when the critical character was changed, and readers could have obtained semantic information from the replacement character.

The presence of a left-of-fixation semantic congruity effect in the total viewing durations of general AOI, and the corresponding effect on L-AOI re-reading, are also consistent with a gradient account of information extraction and with the assumption that word, rather than character,

[2] The semantic congruity of critical character replacement had no effect on R-AOI viewing even when we analysed only those cases in which the eyes landed on the second character of the target word. The numeric effect pattern matched that of the overall data. We considered these data less compelling due to the large variability in this relatively small set of data

recognition is strictly serial in Chinese. Specifically, the total viewing duration data indicate that the meaning of the character to the left-of-fixation could have been accessed – because it formed a word with the next character in the text – and that this occurred relatively late during R-AOI viewing in Experiment 1. Instead of influencing the duration of the first R-AOI fixation, semantic congruity therefore influenced direction of the ensuing saccade so that it resulted in the re-reading of the critical character area.

EXPERIMENT 2

Experiment 2 subjected the unidirectional character processing assumption to more rigorous testing by manipulating the availability of useful phonological and orthographic information to the left of fixation, as this information appears to be sought before character and word meaning is determined. Studies of parafoveal preview benefits that manipulated the right-of-fixation preview of the target word or target character obtained robust benefits from the availability of useful graphemic and phonological information (Liu et al., 2002; Pollatsek et al., 1992; Tsai et al., 2004), indicating that useful information is obtained before the character was fixated. One recent study (White, Bertram, & Hyönä, 2008) also found the semantic preview benefits can accrue from the preview of a word when it is the second constituent word of a spatially unified Finnish compound word, but parafoveal preview of semantically congruent information appears to be absent when words are spatially segmented (Rayner, Balota, & Pollatsek, 1986). Furthermore, studies with English text showed that homophonic and orthographic primes, that are presented at fixation onset prior to the presentation of the corresponding target word, required shorter effective prime durations than semantically related primes (Lee, Rayner, & Pollatsek, 1999). If readers obtained useful orthographic and phonological information from spatially adjacent characters in parallel and if this information was extracted sufficiently early, then orthographic and phonological information available to the left-of-fixation should influence R-AOI viewing. If, however, character processing was strictly unidirectional, then a left-of-fixation character change should not influence R-AOI viewing, irrespective of the time course of character processing.

Four conditions were created in which the replacement character was either a homophone of the critical character or phonologically dissimilar to it. Independent of this, the replacement character and the critical character were either graphemically similar or dissimilar. According to the unidirectional character processing assumption, the phonological properties of the replacement character should not influence first pass R-AOI viewing, as readers should not obtain linguistic information to the left of fixation unless the saccade to the right of the change boundary was due to saccadic overshoot or due to a premature launch. If, however, there was spatial and temporal overlap in the linguistic processing of spatially adjacent characters, as maintained by the attention-gradient conception, then first pass R-AOI reading could be more effective in the homophone than the phonologically dissimilar condition if phonological information was obtained relatively early during Chinese character processing.

Effects of graphemic similarity on first pass R-AOI reading were considered less diagnostic. They are consistent with an attention-gradient conception and they can be reconciled with the unidirectional processing hypothesis as these changes are confounded with visual effects. That is, the replacement of a critical character with a graphemically dissimilar character resulted in a larger physical display change than a replacement with a similar character.

Method

Participants. Twenty-four college students at the National Yang-Ming University, none of whom participated in Experiment 1, were paid to participate in this experiment. All were native speakers of Chinese with normal or corrected vision.

Materials and design. One hundred and twenty sentences were formed for the experiment, each of which contained a two-character target word. All sentences contained between 21–27 characters, and the target word occupied a location between the 11th–20th character positions. Punctuation marks that were used in some of the sentences were at least two characters to the right or left of the target word.

According to the Academia Sinica balanced corpus (1998), the average word frequency of the target word was 14.2 per million. Care was taken to match the character frequency and stroke complexity of the left-of-fixation post-view characters in the four experimental conditions. The average character frequencies of homophonic/graphemically similar, homophonic/graphemically dissimilar, phonologically dissimilar/graphemically similar, and of phonologically and graphemically dissimilar characters were 141.7, 130.7, 113.6, and 165.4 per million, respectively. Most of the graphemically similar characters shared the phonetic but not the smaller semantic radical with the critical character. Graphemically dissimilar characters shared neither the phonetic nor the semantic radical with the critical character. All four types of critical character replacements were closely matched on the average number of strokes (see Table 5). Neither the character frequency nor

TABLE 5
Examples and properties of the post-view stimuli in Experiment 2.

		Critical character replacement			
	First character of the target	*Graphemically similar homophone*	*Graphemically dissimilar homophone*	*Graphemically similar non-homophone*	*Graphemically dissimilar non-homophone*
Example translation	煤 /mei2/	媒 /mei2/	眉 /mei2/	謀 /mou2/	奪 /duo2/
Mean no. of strokes	13.3	13.0	12.0	12.7	12.6
Mean character freq.	126.9	141.7	130.7	113.6	165.4

Note: Character frequency: 1 million characters.

number of character strokes differed significantly across experimental conditions, both $F_2 < 1$.

A boundary was set between the first and second character of the target word. When the eyes crossed the boundary, the critical first character was replaced with one of the characters from the four left-of-fixation conditions. The replacement character changed back to the original character when the eyes moved outside the R-AOI area, irrespective of whether this was due to a right- or left-directed saccade (see Figure 2). Participants read 120 sentences with only one of the conditions presented for each target. The four types of post-view were counterbalanced over participants. There were 30 trials in each condition.

Apparatus, procedure, and data selection. These aspects of Experiment 2 were virtually identical to those of Experiment 1.[3] The selection criteria resulted in the exclusion of 19.1% of the trials.

Results

General AOI. The means and standard errors for first fixation duration, gaze duration, and total viewing duration for the general AOI are shown in Table 6 as a function of the phonological and graphemic similarity between the original and the replacement character.

[3] The probability of fixating at the second character of the target word ranged between 32%–36% in the four experimental conditions. Relative fixation frequency was increased to 61%–64% when the next character was included in the R-AOI.

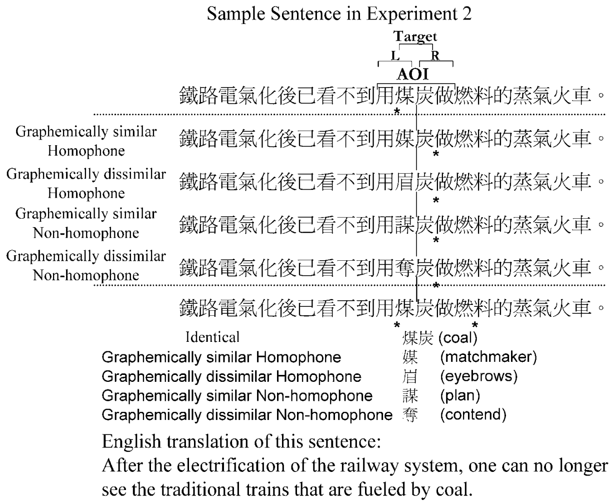

Figure 2. An illustration of a sentence in Experiment 2. Four events in the post-view (C2) conditions. The bar indicates the boundary location, and the asterisk represents eye position. The top line represents the last fixation before the boundary is crossed, and the second, third, fourth, and fifth lines represent the first fixation after the boundary is crossed under different conditions, the graphically similar homophone, graphically dissimilar homophone, graphically similar non-homophone, and graphically dissimilar non-homophone conditions respectively. The bottom line represents the first fixation after readers' eyes left to the R-AOI location.

First fixation durations revealed a negligible effect of graphemic and phonological similarity, F_1, $F_2 < 1$, and F_1, $F_2 < 1$, respectively. The interaction of phonological and graphemic effects was also negligible, all

TABLE 6

Eye movement measures for AOI as a function of post-view type in Experiment 2. First fixations, gaze durations and total viewing durations are measured in ms. Standard errors of the mean are shown in parentheses.

		Critical character replacement		
	Post-view type	*Graphemically similar*	*Graphemically dissimilar*	*Mean*
First fixation duration	Homophone	261 (8)	260 (10)	261
	Non-homophone	260 (9)	251 (8)	255
	Mean	260	255	
Gaze duration	Homophone	462 (27)	490 (34)	476
	Non-homophone	461 (28)	456 (24)	459
	Mean	462	473	
Total viewing duration	Homophone	552 (40)	553 (39)	553
	Non-homophone	532 (30)	540 (28)	536
	Mean	542	546	

$F < 1$. Gaze duration was, however, significantly *longer* (by 17 ms) in the homophonic than the phonologically dissimilar condition, $F_1(1, 23) = 4.595$, $p < .05$; $F_2(1, 118) = 3.733$, $p = .056$. Neither the main effect of graphemic similarity nor the interaction of phonological and graphemic effects approached significance, all $F < 1$. Re-reading substantially increased the variability, and the 17 ms longer total viewing durations in homophonic than the phonologically dissimilar condition did not approach significance, all $F < 1$. Once more, neither the effect of graphemic similarity nor the interaction of phonological with graphemic similarity approached significance, all $F < 1$.

R-AOI. First pass right-side AOI viewing is shown as a function of phonological and graphemic similarity in Figure 3. First fixation duration was 11 ms *longer* when the left-of-fixation replacement character and the originally viewed character were homophones than when they were phonologically dissimilar, $F_1(1, 23) = 5.784$, $p < .05$; $F_2(1, 118) = 3.761$, $p < .06$. The marginally reliable F_2 effect was statistically significant, $F_2(1, 106) = 3.92$, $p < .05$, robust, when 12 items were removed with fewer than two data points in each of the four experimental conditions. Gaze durations were more variable than first fixation durations, and a corresponding 11 ms effect was marginally significant over participants, $F_1(1, 23) = 3.648$, $p = .07$, but not over items, $F_2(1, 118) = 2.472$, $p = .119$. The effect of graphemic similarity, by contrast, was neither reliable for first fixation durations nor

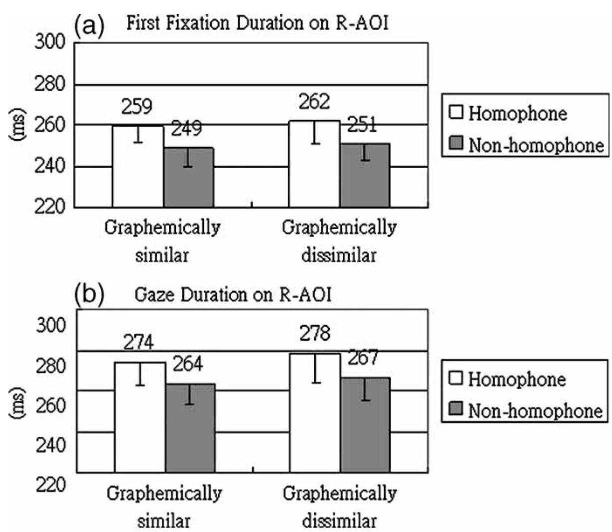

Figure 3. First fixation durations (a) and gaze durations (b) as the function of graphical and phonological similarity in Experiment 2.

TABLE 7
Eye movement measures for the R-AOI as a function of post-view type in Experiment 2 (when removing following trials of re-reading on L-AOI). First fixations and gaze durations of R-AOI are measured in ms. Standard errors of the mean are shown in parentheses.

		Critical character replacement		
Removing re-reading	*Post-view type*	*Graphemically similar*	*Graphemically dissimilar*	*Mean*
First fixation duration	Homophone	255 (8)	261 (10)	258
	Non-homophone	244 (9)	249 (9)	247
	Mean	250	255	
Gaze duration	Homophone	271 (12)	281 (15)	276
	Non-homophone	258 (10)	261 (11)	259
	Mean	265	271	

gaze durations, all $F < 1$. Effects of the critical character manipulation did not spill over into the reading of text following the R-AOI, all $F < 1$ (see Table 8).

Two supplementary analyses were applied to R-AOI first fixation duration and gaze duration to determine whether the negative effect of phonological similarity was due to saccadic overshoot or premature saccades to the right of the change boundary. For this, all trials were removed from R-AOI analysis in which the eyes regressed out of this area. With potential effects of saccadic error removed, first fixation durations were 11 ms and gaze durations were 17 ms longer in the homophone than the phonologically dissimilar condition, $F_1(2, 46) = 5.742$, $p < .05$, and $F_1(2, 46) = 6.408$, $p < .05$, respectively (see Table 7).[4] The phonological properties of the replacement character thus influenced R-AOI reading even when the saccade to the right of the change boundary was not due to overshoot or a premature launch.

L-AOI. Effects of phonological and graphemic similarity on L-AOI re-reading are shown in Table 8. In contrast to R-AOI reading, re-inspection was influenced by graphemical similarity. That is, re-inspection rate was slightly higher in the graphemically dissimilar than the similar condition, $F_1(1, 23) = 1.967$, $p > .15$; $F_2(1, 118) = 3.159$, $p = .078$, especially when the replacement character was a homophone, $F_1(2, 46) = 4.257$, $p = .050$; $F_2(2, 236) = 0.902$, $p > .3$. Moreover, second-pass fixation duration (or second-pass time; Binder et al., 1999) was significantly longer in the graphemically

[4] The by-item analysis was not possible here due to the limited number of observations per condition.

TABLE 8

Eye movement measures for the L-AOI as a function of post-view type in Experiment 2. Second-pass time on L-AOI (in ms), regression rate to L-AOI (in percentage values) and spillover fixation durations of R-AOI (in ms). Standard errors of the mean are shown in parentheses.

		Critical character replacement		
	Post-view type	*Graphemically similar*	*Graphemically dissimilar*	*Mean*
Regression rate to L-AOI	Homophone	4.1 (1.2)	8.0 (2.5)	6.0
	Non-homophone	5.6 (1.5)	5.1 (1.7)	5.3
	Mean	4.8	6.5	
Second-pass time on L-AOI	Homophone	9.3 (4.0)	26.3 (8.8)	17.8
	Non-homophone	14.7 (4.7)	18.1 (7.7)	16.4
	Mean	12.0	22.2	
Spillover fixation duration	Homophone	273 (11)	279 (11)	276
	Non-homophone	264 (9)	278 (10)	271
	Mean	268	278	

dissimilar than the similar condition, $F_1(1, 23) = 4.411$, $p < .05$; $F_2(1, 118) = 7.758$, $p < .01$. Once more, the effect of graphemic similarity tended to be larger in the homophone condition, $F_1(2, 46) = 6.266$, $p < .05$; $F_2(2, 236) = 1.544$, $p > .2$.

Discussion

The manipulation of the phonological properties of a replacement character to the left of fixation increased the duration of the following fixation. It was longer when the critical character and its replacement were homophones than when they were phonologically dissimilar. The effect was statistically reliable over participants and items with three or more observations in each condition. Furthermore, supplementary analyses showed that the numeric size of the inhibitory effect of phonological similarity did not abate when trials in which the eyes regressed from the R-AOI toward the critical character location were removed. Graphemic properties of the left-of-fixation replacement character had virtually no effect on duration of the following fixation, by contrast. Instead, this type of change primarily influenced the re-inspection of the L-AOI.

The robustness of the phonological similarity effect during R-AOI viewing is inconsistent with the strictly unidirectional character processing assumption. Furthermore, the phonological similarity of a left-of-fixation character had a deleterious effect on the duration of the first fixation during R-AOI viewing even when all cases with regressions toward the critical character were removed. It is, therefore, unlikely that the phonological similarity effect can be attributed to saccadic overshoot or to prematurely launched saccades. If this had been the case, then the effect of phonological similarity on the duration of the following R-AOI fixation should have decreased when trials were removed in which first pass R-AOI viewing was followed by a re-inspection of the L-AOI.

Although Experiment 2 did not include a control condition without a left-of-fixation display change, it appears exceedingly unlikely that the homophone effect is a byproduct of eye-movement-contingent display changes. Trials were excluded in which a change took place after – rather than during – the saccade across the display change boundary. Although some participants noticed a display change on occasion this did not eliminate the effect of the replacement character's phonological properties on the following R-AOI fixation. Critically, R-AOI viewing was not influenced by the graphemic similarity manipulation, even though the physical stimulus change was larger in the graphemically dissimilar than the similar condition. Consequently, effects of homophony on the duration of the first R-AOI fixation were not an artifact of display changes.

The duration of the first R-AOI fixation increased when the replacement character and the critical character were homophones. Prior manipulations of parafoveally visible words and Chinese characters have shown the opposite effect pattern. Specifically, a right-side preview of a Chinese target character that was a homophone of the target *decreased* the time spent viewing the target when it was subsequently fixated relative to a non-homophonic control character. In view of this, we anticipated benefits, rather than costs, from a homophonic left-of-fixation 'post-view'.

Why did a contextually incongruent homophonic post-view character incur costs? The current study cannot provide a definitive answer to this question. However, differences between right-of-fixation parafoveal previews and left-of-fixation post-views offer some viable explanations. A previewed character to the right of fixation is yet to be identified and yet to be integrated into sentence context. At this early stage of parafoveal progressing, specification of a character's sound code occurs in the absence of any knowledge of character meaning. In this case, knowledge of a character's phonological code facilitates the accessing of meaning when the character is subsequently viewed. In contrast to this, a character's phonological and semantic representation may be established by the time the eyes move to the right of it. Similar to its preview, a homophonic post-view could still facilitate the pre-semantic processing of a character at that location, as the phonological code remains unchanged. In the post-view condition, however, this facilitation will provide access to a character meaning which is incongruent with the meaning of the previously identified character at that location.

The duration of the first R-AOI fixation could also be longer in the homophonic condition than in the phonologically dissimilar condition because homophonic post-views provided information that could be used to 'repair' the meaning of the contextually incongruent replacement character. Using sentences with semantically incongruent English words, several studies (Daneman, Reingold, & Davidson, 1995; Inhoff & Topolski, 1994) showed that readers could infer a context-consistent meaning for incongruent words and pseudowords when these stimuli were homophones of contextually congruent words, e.g., blew jeans or brane surgeon were 'repaired' to mean blue jeans and brain surgeon, respectively. This inference may take time and account for the deleterious effect of homophony on R-AOI viewing. Consistent with this particular view, several studies have shown that character phonology assumes an important role when Chinese text is read for comprehension (Feng, Miller, Shu, & Zhang, 2001; Tsai et al., 2004; Tzeng, Hung, & Wang, 1977; Zhang & Perfetti, 1993).

GENERAL DISCUSSION

The current study used an eye-movement-contingent display change technique to examine the validity of the unidirectional character processing assumption during the reading of Chinese text, according to which readers identify visually distinct character units in strictly serial order. In Experiment 1, a critical character was replaced with a contextually congruent or incongruent character when the eyes moved to its right. Consistent with the unidirectional character processing assumption, the semantic congruency of a replaced critical character did not significantly alter the duration of the R-AOI fixation that followed the replacement. The meaning of the replacement character numerically influenced re-reading of the L-AOI area with the changed character, however, which consumed more time in the semantically incongruent than the congruent condition.

Binder et al. (1999) obtained similar results with English text, with more frequent and longer-duration re-inspections when the target word's temporary left-of-fixation replacement was semantically incongruent than when it was congruent. Rather than concluding that this finding contravenes the unidirectional word processing assumption (for English text), Binder et al. (1999) suggested that it was due to computational errors, i.e., instances in which the eyes overshot the target or moved prematurely to the right of it. The same explanation can be used to account for the re-inspection of the critical character area in Experiment 1.

Nevertheless, two other accounts could not be ruled out. The meaning of the replacement character to the left of fixation could have influenced re-reading because readers obtained linguistic information from more than one spatially adjacent Chinese character in parallel. Alternatively, readers could have sought useful linguistic information from the changed character because it was part of a larger unit – the word. The processing of the word was not completed by the time the eyes crossed the character-change boundary.

The results of Experiment 2 were more decisive. The replacement of a critical character with a contextually incongruent but homophonic character when the eyes moved to the right of it increased the duration of the following R-AOI fixation. Moreover, the magnitude of the homophonic post-view effect increased numerically when trials were removed in which first-pass R-AOI viewing was followed by a regression. These results provide compelling evidence against a strictly unidirectional character processing assumption. Two other accounts are compatible with the data. First, Chinese readers may seek linguistic information from the character constituents of individual words, the identification of which may progress serially with word order. In the current study, all replacement characters were part of a legal two-character word that included the character to the right of fixation. That is, processing of the left character may not have been completed when the eyes crossed the character change boundary because recognition of the full two-character word was still in progress. Indirect support for this conception is provided by a recent version of the E-Z reader model (Rayner, Li, & Pollatsek, 2007). It successfully simulated oculomotor activity during Chinese sentence reading based on the assumption that word recognition was strictly unidirectional. Notably, the addition of a parameter for character processing did not improve the model. The claim that the extraction of linguistic information progresses unidirectionally from one word to the next in Chinese raises, however, the question of how word boundaries are determined in the absence of any physical marking. Since there is some variability in word length, Chinese readers cannot assume that to-be-recognised words will contain a particular number of characters.

The second viable processing strategy is that during each fixation, useful linguistic information may be sought from several spatially adjacent characters in parallel, including the fixated character, the character to its left, and one or two characters to its right, and useful information may be sought from a particular character during more than one fixation. This may yield tentative word groupings that could be identified in sequence.

The parallel processing of more than one meaning-conveying linguistic unit has also been demonstrated in other languages when these linguistic units were not physically separated. In Bertram and Hyönä's (2003) study, the word frequency of Finnish compound words influenced the duration of the first compound fixation when the compound unit consisted of two short words. The effect pattern changed when the compound word consisted of two long words. In this case, it was the frequency of the first constituent word that determined the duration of the first compound fixation. Bertram and Hyönä (2003) concluded that the constituent words of a short compound were processed in parallel and that the constituents of a long compound were processed in sequence. The meaning of the second constituent of a short compound word influenced the duration of the first compound fixation in a more recent study (Inhoff, Starr, Solomon, & Placke, 2008) also suggesting the processing of adjoining semantic units can overlap in time.

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