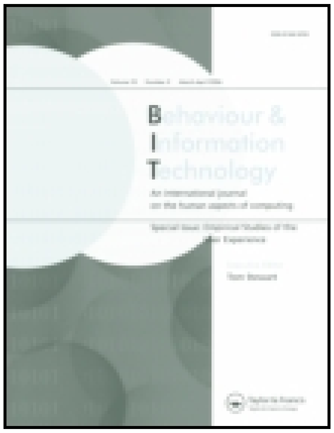

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Effects of typographic variables on eye-movement measures in reading Chinese from a screen

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To investigate the most efficient way to represent text in reading Chinese on computer displays, three typographic variables, character size (41′ arc/24 pixels and 60′ arc/32 pixels), character spacing (1/4 and 1/8 character width) and font type (Kai and Ming), were manipulated. Results showed that the reading speed for Chinese characters of Kai type in 24 pixels with 1/8 character spacing was the shortest. Character size significantly affected overall reading speed; in specific, text in 24-pixel characters was read faster than text in 32-pixel characters. Further eye-movement analyses revealed that text in smaller-sized characters had longer fixation duration, fewer fixations and fewer regressions than text in larger-sized characters. The interaction between character spacing and font type was observed on overall reading efficiency and on some eye-movement measures, which suggests that different character spacings should be considered in different font types for more efficient reading. Generally, characters in Kai font were easier to read with 1/8 character spacing than with 1/4 character spacing. The relationship between eye-movement measures and overall reading efficiency was further discussed.

Keywords: character size; character spacing; font type; eye-movement measures

1. Introduction

Reading on the computer has increased rapidly. As people become more comfortable with and adept at reading on the computer screen, investigation of factors that influence the effectiveness of reading also becomes more relevant. Many typographic variables can influence how fluently text is read on computer screens. Such variables include character font type and size, line length, columns, window size and interlinear spacing (e.g. Mills and Weldon 1987, Dyson 2004). Although there has been extensive empirical research examining the effects of different display factors on screen reading in English (e.g. Mills and Weldon 1987, Muter 1996, Boyarski *et al*. 1998, Bernard *et al*. 2002, 2003, Dyson 2004), only a few investigated how these factors affect the efficiency of screen reading in Chinese (e.g. Chan and Lee 2005). The writing system of English is vastly different from that of Chinese. Therefore, findings from studies on reading in English may not generalise to reading in Chinese. Given that the Chinese writing system is used by one-quarter of the world's population (Taylor and Taylor 1995), further research on this subject not only has a wide appeal, but also gives a more complete picture to the underlying processes underlying screen reading.

English belongs to an alphabetic system in which the writing unit is a word. Words are composed of equally spaced letters, and different words are separated by additional spacing between them to form sentences. In contrast, the logographic writing system in Chinese uses characters as the writing unit. Each character occupies an equal-sized rectangular region composed of component radicals (units of combined strokes). Individual characters vary greatly in complexity in terms of the number of strokes. However, no matter how complex it is, each character is confined into a constant, box-shaped area. The visual structure of Chinese characters makes them appear as integrated, isolated visual objects, such that they can be regarded as the perceptual unit for reading (Tsai and McConkie 2003). A Chinese word can consist of one, two, or even more characters. However, unlike in English, there is uniform spacing between all of the characters in a sentence, regardless of whether one or more words span multiple characters. In other words, characters are separated by space of an equal size, whether the characters are part of the same word or different words. Traditionally, written or printed Chinese text is organised in top-to-bottom vertical strings of characters arranged from right to left. However, similar to English text, the majority of modern Chinese text on

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computer displays is presented in left-to-right horizontal lines arranged from top to bottom, even though the traditional vertical layout is still possible. Despite the fact that there is no obvious additional spacing marking word boundaries between adjacent characters in Chinese text, reading rates are comparable for Chinese (580 characters per minute, equivalent to 390 words per minute (WPM)) and for English (380 WPM) (Sun *et al.* 1985). However, the overall size of the perceptual span is influenced by different writing systems. The perceptual span of alphabetical orthographies (e.g. English) is about three to four letters to the left of fixation and about 14-15 letter spaces to the right of fixation. In Chinese, the asymmetric perceptual span extends from one character space left of fixation to three character spaces to the right (Rayner 1998).

Past studies exploring screen reading have examined how different typographic variables affect the legibility and readability of text. In these studies, legibility generally refers to how easy a text item (e.g. a single letter or a small array of letters) is identified, whereas readability refers to how easy it is to comprehend a text structure with higher complexity (e.g. words, lines or pages of text; Mills and Weldon 1987). Legibility is usually evaluated by identification tasks in which letters/characters are presented with decreased visibility, and thresholds for correct detection are determined (e.g. Chi *et al.* 2003, Sheedy *et al.* 2005). These tasks provide information regarding how easily the visual system detects and recognises letters/characters in earlier stages of reading. However, these tasks do not involve all the processes required in normal reading. In contrast, text readability is usually assessed by tasks that measure reading comprehension and/or reading speed (e.g. Bernard *et al.* 2002, 2003, Chan and Lee 2005). Although these tasks give crude overall measures of reading efficiency, they do not reveal any further details of the underlying processes during reading.

In the present study, we aimed to determine the best combination of typographical factors to present Chinese text on the computer screen (e.g. in online documents) for optimal screen reading. We explored the effects of three typographic variables on screen reading in Chinese. These variables included character size, character spacing and font type. In order to examine how information is processed in normal screen reading in greater detail, we combined the traditional readability task with the eye-tracking technique. Before introducing the experimental details, the effects of character size, character spacing and font type on character legibility and text readability will be briefly reviewed below, followed by an overview of the eye-movement measures used in the present study.

1.1. *The effects of character size, character spacing and font type on text legibility and readability*

1.1.1. *Character size*

The legibility of a character is directly influenced by the size of the character. For reasonable legibility, it is recommended that the size of a English character on visual display terminals (VDTs) should span a minimum visual angle of 11′ or 12′ arc (Snyder and Taylor 1979). Under situations where legibility is important, the minimum character height for a capital letter should be 16′ arc for reading tasks, with a preferred character height of 20–22′ arc (ANSI/HFS 1988). At a normal reading distance of 500 mm, these standards translate into a minimum height of 2.3 mm and a preferred height of 2.9–3.3 mm on VDTs.

The effect of character size on text readability is more complicated. On the one hand, larger characters are more legible and thus may speed up the initial stages in reading by reducing the processing time required to recognise the characters. On the other hand, smaller characters help to maximise the information within a given reading window, which, in turn, helps to facilitate the speed of reading. Therefore, the ideal character size that optimises text readability should be a size that is large enough to be clearly legible, yet small enough to pack in the maximal amount of information in the same space. In theory, characters larger or smaller than this optimal size should render the readability of text, thus reducing reading performance and slowing down reading speed.

This bi-directional effect of character size has been demonstrated with printed text, for which font height greater or smaller than 3.1–3.6 mm (9–10 point [pt] font type) both lead to slower reading. For screen reading, a previous study showed that down-scaling of the character size from a height of 24.3 to 7.6 mm resulted in faster speed for reading (Snyder and Maddox 1978). With a viewing distance of 1020 mm in the study, these character sizes fell well above the range of preferred character height (5.9–6.7 mm) for optimal text legibility. The results suggest that the optimal character size for reading should be smaller than the smallest character size investigated in this study, and possibly similar to the preferred/minimal recommended size for reading. Hypothetically, if the researchers had extended the range to include character sizes below the optimal reading size, they might find the reading speed to start dropping again, as the character size scaled further down below the optimal reading size.

In comparison to English characters, Chinese characters are visually more complex and typically encompass more structural details within each character. Correspondingly, the minimal recommended character size for good legibility goes up to 33′ arc, a size that better resolves the extra structural details within the characters (Wu *et al*. 2006). With regard to readability of Chinese text, the effect of font size has been previously examined with 10- and 14-pt font sizes for displaying text on computer screens. These font sizes corresponded to 27′ and 38′ arc, respectively, with a viewing distance of 450 mm in the study. It was found that passages in the larger characters were read faster and comprehended better than those in the smaller characters (Chan and Lee 2005). However, these results on text readability might have been confounded by character legibility, because the smaller font size that was read slower and was more difficult to comprehend also happened to fall below the recommended font size for optimal legibility. In the present study, we investigated the effect of character size within the range of legible sizes. The character sizes chosen are 41′ and 60′ arc. The larger one is significantly larger than the minimal recommended character size. If there is an optimal size for reading, it is expected that the passages with 41′ arc character size will produce better performance than those with 60′ arc.

1.1.2. *Character spacing*

Another variable manipulated in the present study was character spacing. Prior research has indicated that the 0.57 mm spacing with 1.14 mm character width is the most distinguishable spacing in English (Snyder and Maddox 1978). In Chinese, Hwang *et al*. (1988) found that 0.61 or 1.21 mm spacing with 4.84 mm character size is most legible on VDTs. In the present study, because the character sizes are varied at two levels (24 and 32 pixels, which equal to 41′ and 60′ arc, respectively), instead of using the exact character spacing, the character spacing is defined by the ratio of character width. According to Hwang *et al*.' s study, two levels of ratio, 1/4 and 1/8 character width, are selected.

1.1.3. *Font type*

The typeface of a character is one of the most important typographic variables that influence character legibility (Snyder and Taylor 1979) and text readability (Bernard *et al*. 2003). Several font types for Chinese characters such as Ming, Kai, Li, Hei and Xing are commonly used in print materials and on VDT display (Zhan 1994). Among the great variety of font typefaces available for presenting Chinese text, Ming (for books and articles; default typeface for MS Windows) and Kai (for documents) are the most frequently used (Chang 2005). Research investigating the subjective preference for different typefaces showed that Kai is aesthetically more pleasing to readers than Ming (Shieh *et al*. 1997). However, previous studies have shown that characters in Ming are more legible than those in Kai (Shieh *et al*. 1997, Cai *et al*. 2001). Shieh *et al*. (1997) found that participants could identify the characters more correctly in Ming type than in Kai type. Cai *et al*. (2001) used the recognition task to test the legibility threshold of three font types, namely, Ming, Kai and Li styles. It was found that Ming is the most legible one, followed by Kai and then by Li. However, Wang and Chen (2003) did not find any significant difference between Ming and Kai types on reading performance. The effect of Ming and Kai type on readability still needs further examination.

Some distinct features, such as strokes, balance and bold, are different between characters of Ming and Kai type. The most important difference might be the compactness. At the same font size, the area that Kai occupied is smaller than that of Ming (see Figure 1). Cai *et al*. (2001) compared six typographic measures (height, width, width–height ratio, area, stroke width and stroke density) of 198 characters in Ming and Kai types. Although the characters of the two types are confined to a fixed square area for a particular character size, it was found that the Ming characters had larger height (9.59%), width (9.70%) and area (21.29%) compared with the Kai characters. Since the Kai characters are thinner and smaller than the Ming characters, it is reasonable to assume that smaller character spacing fits better with the Kai type. In other words, an interaction between font type and character spacing is expected. The finding that characters in Ming are more legible than those in Kai can be explained by the compactness difference between Ming and Kai types. If there is an interaction between font type and character spacing in normal reading process, it can provide a possible explanation why characters in Ming type do not necessarily lead to better reading performance than those in Kai type.

In summary, in order to investigate the most efficient way to represent text in reading Chinese on

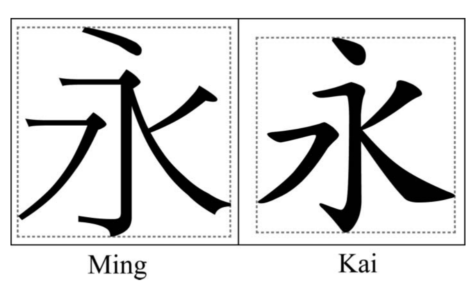

Figure 1. Two different font types we used in this study, Ming and Kai. The black solid line represents the character size. The gray dashed line represents the exact area that a character occupies.

computer displays, character size (24 and 32 pixels), character spacing (1/4 and 1/8 character width) and font type (Kai and Ming) are manipulated in the present study. It is expected that the more optimal character size (24 pixels) would result in better reading performance. Furthermore, since the Kai characters are thinner and smaller than the Ming characters, an interaction between font type and character spacing is also expected.

1.2. Eye-movement measures

Although data about reading Chinese from the screen are available, the more delicate reading process in normal reading influenced by typographical factors cannot be fully revealed by observing the total reading time in readability tasks. In order to examine more detailed information processes in normal reading, eye-movement patterns were observed with a readability task in the present study. During reading, a person's eyes make a series of fast jumps (saccades) along the line of text. The mean saccade size is 7–9 letter spaces in English (Rayner 1998) and 2.6 characters in Chinese (Sun *et al.* 1985, Yang and McConkie 1999). Between saccades, the eyes remain relatively still, fixated for about 200-250 ms. When the reader encounters difficulty processing text, their eyes tend to move back to a previously read region, either to an area to the left of the text line or back to previously read lines. These types of eye movement are referred to as regressions, which make up about 10–15% of saccades in reading (Rayner 1998).

Previous studies have demonstrated that typograpgic variables that affect character legibility and text readability also influence eye-movement patterns during reading (Tinker 1963, Kolers *et al.* 1981, Morrison and Inhoff 1981, Morrison and Rayner 1981, Beymer *et al.* 2008). For example, when researchers manipulated the number of character contained in each line of text, smaller characters (70 characters per line) resulted in more efficient reading than larger characters (35 characters per line). In terms of eye-movement patterns, participants showed fewer fixations and longer fixation durations while reading text in smaller characters than that in bigger characters (Kolers *et al.* 1981). The increased fixation duration for smaller-sized characters may be caused by reduced character legibility, and the increased fixation number for larger-sized character may be due to a smaller perceptual span (Paterson and Tinker 1947, Tinker and Paterson 1955). A perceptual span is defined as the amount of text information that the reader effectively processes during an individual fixation (Paterson and Tinker 1947). Tinker argued that more legible text allows readers a wider perceptual span, which requires fewer fixations and allows longer saccades. According to Tinker's suggestion, eye-movement measures could reflect the influences of visual configuration in reading material, such as text legibility.

A number of eye-movement studies have examined how inserting space between words or characters in Chinese influences reading (Inhoff *et al.* 1997, Bai *et al.* 2008). Bai *et al.* (2008) found that sentences with unfamiliar word spaced format were as easy to read as normal spaced text. Furthermore, text with a space between every character produced longer reading times than normal unspaced text. These results reflected on the total reading time, fixation duration, number of fixations and saccade length. However, these studies were not aimed to examine the effects of typographic variables in reading Chinese. Obviously, more studies with eye-movement measures are needed to approach some of the subtler interface usability issues in screen design or text format.

In the present study, eye movements were recorded to observe the onscreen Chinese reading process. Eye-movement measures can provide more detailed information about the influences of visual configuration of reading material in the reading process. Consequently, the effects of typographic variables on total reading time can be attributed to or explained in its specific components, such as fixation duration, number of fixations, saccade length, and others (Rayner 1978). The readability and eye-movement measures used in the present study are defined below, along with the predicted effects of the typographic variables manipulated.

(1) Total reading time per passage: The total reading time of a passage is a typical measure of performance for readability. At the same comprehension level, reading efficiency is reflected by the reading speed of a passage.
(2) Number of fixations: The total number of valid fixations to read a passage. In general, more legible text allows readers a wider perceptual span, which requires fewer fixations. However, the fixation number is expected to be more for larger-sized characters because of a smaller perceptual span (Tinker 1963).
(3) First fixation duration: The duration of the first fixation on the target character, which has not been passed before. It is assumed that a longer fixation duration reflects that more detailed information is absorbed or required to be absorbed by the reader to process the information further (Kolers *et al.* 1981). Inhoff (1984) further suggested that the first fixation duration is a measure that reflects the early lexical access processes. Thus, first fixation duration is expected to be longer for smaller-sized characters because of reduced character visibility.

(4) Gaze duration: The summed duration of all fixations on the target character prior to any movement away from the target character, which has not been passed before. The gaze duration measure tends to correlate with the first fixation duration. However, the gaze duration measure reflects all processing before the readers move their eyes away from the character, which may include various integrative processes after the first fixation (Just and Carpenter 1980). It is hypothesised that the visual configuration variables manipulated in the present study should have more influence on the earlier processes instead of the later integrative processes. Therefore, it is expected that the effects of the manipulated typographic variables are similar in first fixation duration and gaze duration.
(5) Saccade length: The average number of characters between two valid fixations. It is reasonable to assume that typographic variables such as character size or character spacing affect saccade length. Saccade length is expected to be shorter for larger-sized characters or larger character spacing due to a smaller perceptual span (Tinker 1963). However, O'Regan (1980) argued that the number of characters is the critical determinant of saccade length. In other words, saccades should scale up for larger characters. Therefore, according to O'Regan's argument, the saccade length should not be affected by character size or character spacing.
(6) Overall regression rate: The proportion of the regressive fixation number to the total valid fixation number. More difficult texts usually produce more regressive saccades (e.g. Rayner 1998), which can be indicated by a higher regression rate.

To summarise, the main aim of this study was to analyse eye-movement patterns for the effects of character spacing, character size and font type in reading Chinese on computer displays. Other than the objective measures, subjective preferences toward the task factors were also collected from the readers. The study should lead to some useful design recommendations for screen display format and layout to improve reading performance.

2. Method

2.1. Participants

Participants included 64 native Chinese speakers (31 females and 33 males, age 19-24 years) from National Chengchi University, Taipei, with normal or corrected-to-normal vision. Each participant received either course credit or money for his/her participation.

2.2. Materials and experimental design

The experimental design included three typographic variables, character size, character spacing and font type. With two levels of manipulation in each within-participant variable, each participant was required to read a total of eight passages, each with a unique combination of the three typographic variables. Characters within each passage were presented in either a large (60′ arc/32 pixels) or a small (41′ arc/24 pixels) size, defined as the visual angle of the retinal image occupied by the default character area. Both sizes were larger than the legible size recommended for presenting Chinese (i.e. 33′ arc). Characters were separated by either large or small spacing (1/4 or 1/8 of the character width). Two common font typefaces, Ming and Kai, were chosen for comparison. An example of the text in the eight typographic conditions is shown in Figure 2.

The reading materials were eight narrative passages selected from the Academia Sinica Corpus ranging

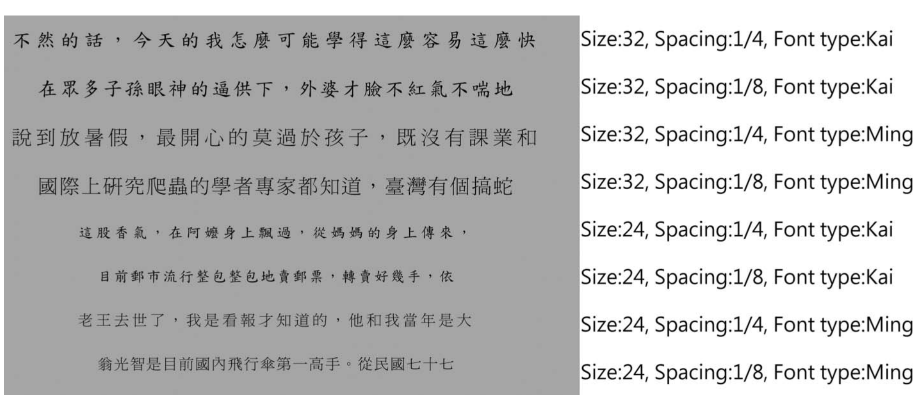

Figure 2. Examples of experimental materials in eight conditions.

from 1866 to 2358 Chinese characters. The difficulty and emotional levels of the eight selected passages were rated by 120 undergraduate students prior to the study. No significant difference was found among these passages. Each passage was divided into different pages for presentation on the computer screen. Four lines of text were shown on each page. Because all lines consisted of 22 characters, the same passage always spanned the same number of pages regardless of the different typographic conditions. The eight passages spanned a range of 18–21 pages. To continue reading onto the next page, participants were told to press a button. The assignment of passages and the serial order of the eight reading conditions were counterbalanced between participants by use of Latin square. The dependent variables included six eye-movement indicators (total reading time per passage, number of fixations, first fixation duration, gaze duration, saccade length and regression rate), comprehension score and preference rating.

2.3. Apparatus

Passages were presented on a 19-in. (365 mm × 275 mm) Viewsonic cathode ray tube (CRT) monitor (1024 × 768 pixels) controlled by an IBM-compatible Intel Core 2 Duo computer. Text presentation was controlled by a manual program running on Matlab with Psychophysics Toolbox extensions (Brainard 1997, Pelli 1997). Participants were seated 740 mm from the screen, and head movements were minimised through the use of a chin rest. Eye movements were recorded with an iView X Hi-Speed System manufactured by Senso-Motoric Instruments (SMI). The eye tracker sampled at 500 Hz and tracked both the pupil and corneal reflection. Eye movements were recorded from the dominant eye, although viewing was binocular.

2.4. Procedure

Participants were seated on a chair facing a computer monitor with the eye-camera positioned on their head and adjusted for optimal tracking. Participants were calibrated with a standard 9-pt grid, and calibration accuracy was checked by validation with another 9-pt grid. After calibration, participants were instructed to read the passages silently at a normal pace and to indicate that they had finished reading by pressing a button on the mouse. Participants were told to answer four yes/no comprehension questions following every passage, and to indicate their preference for the text format on a six-point scale (1 – *least preferred* to 6 – *most preferred*).

3. Results

The eye-movement data from one participant were excluded from the analyses due to a recording error. Fixations that fell outside the upper and lower 40% pixels of the height of the character were treated as invalid fixations. Thirty-six per cent of the total fixations across the subjects were excluded from the analyses. The means and standard errors of all the dependent measures in the eight presentation conditions are listed in Table 1. To examine the effects of the typographic variables, each dependent variable was entered into a 2 character size × 2 character spacing × 2 font type repeated-measures analyses of variance (ANOVA).

3.1. Total reading time and number of fixations per passage

Analyses of total reading time and number of fixations per passage showed similar patterns. For total reading time, a significant main effect in character size showed that the total reading time was shorter for 24-pixel characters ($M = 84{,}977.921$ ms) compared with 32-pixel characters ($M = 10{,}3382.413$ ms) [$F_{(1,62)} = 94.133$, $p < 0.0001$]. An interaction between character spacing and font type [$F_{(1,62)} = 8.139$, $p < 0.01$] was also found. The multiple comparisons (Tukey's honestly significant difference (HSD)) were further used to test the interaction effect. The result indicated that total reading time was shorter for text with 1/8 character spacing than with 1/4 character spacing in Kai [$F_{(1,62)} = 6.351$, $p < 0.05$], and shorter in Kai than in Ming with 1/8 character spacing [$F_{(1,62)} = 4.211$, $p < 0.05$] (Figure 3).

For number of fixations, a significant main effect was found in character size [$F_{(1,62)} = 178.610$, $p < 0.0001$]. A higher frequency of fixations was found when participants read text in 32-pixel characters ($M = 471.306$) than in 24-pixel characters ($M = 370.258$). A significant interaction between character spacing and font type was also found [$F_{(1,62)} = 5.612$, $p < 0.05$]. Further analyses indicated that when passages were in Kai, a higher frequency of fixations was observed with 1/4 character spacing than with 1/8 character spacing [$F_{(1,62)} = 7.622$, $p < 0.01$]. When passages were in Ming, character spacing did not make a difference (Figure 4).

3.2. First fixation duration and gaze duration

The results of first fixation duration and gaze duration also showed similar patterns. For the first fixation duration, significant main effects were found in character size [$F_{(1,62)} = 90.200$, $p < 0.0001$] and

Table 1. The mean and standard error of 8 dependent variables in eight conditions.

Character size	32				24			
Dependent variables in eight condtions / Character spacing	1/4		1/8		1/4		1/8	
Font type	Kai	Ming	Kai	Ming	Kai	Ming	Kai	Ming
Total reading time per passage (ms)	109436.762 (5501.814)	102438.063 (5089.202)	100110.254 (4598.755)	101544.571 (4985.937)	86010.286 (4655.600)	83882.413 (4531.269)	77951.778 (3919.8860)	92067.206 (5336.963)
Number of fixation per passage	497.143 (23.125)	471.603 (20.576)	456.460 (19.287)	460.016 (19.943)	378.302 (18.642)	370.746 (19.198)	342.413 (16.767)	389.571 (20.356)
First fixation duration (ms)	222.259 (2.966)	219.117 (2.716)	222.900 (2.951)	223.013 (3.230)	231.233 (3.191)	230.674 (3.256)	232.094 (3.048)	237.333 (3.041)
Gaze duration (ms)	239.613 (3.665)	234.780 (3.349)	238.675 (3.474)	238.620 (3.796)	244.979 (3.660)	242.982 (3.575)	245.162 (3.436)	251.469 (3.526)
Saccade length	3.686 (0.106)	3.813 (0.109)	3.801 (0.105)	3.938 (0.105)	3.758 (0.117)	3.844 (0.098)	3.926 (0.105)	3.976 (0.106)
Regression rate (%)	0.139 (0.006)	0.142 (0.006)	0.140 (0.007)	0.140 (0.007)	0.126 (0.006)	0.121 (0.005)	0.122 (0.006)	0.126 (0.006)
Comprehension score	0.848 (0.024)	0.883 (0.017)	0.891 (0.018)	0.879 (0.022)	0.855 (0.025)	0.871 (0.022)	0.859 (0.021)	0.863 (0.021)
Preference rating	4.219 (0.106)	3.969 (0.116)	4.250 (0.089)	3.938 (0.107)	3.750 (0.126)	3.922 (0.095)	3.656 (0.122)	3.813 (0.124)

Note: The values in parentheses are the standard errors of the dependent variables.

character spacing [$F_{(1,62)} = 8.863$, $p < 0.005$]. Specifically, the first fixation duration was shorter for 32-pixel characters ($M = 221.822$ ms) than for 24-pixel characters ($M = 232.833$ ms), and it was shorter in 1/4 character spacing ($M = 225.821$ ms) than in 1/8 character spacing ($M = 228.835$ ms). The interaction between character size and font type [$F_{(1,62)} = 4.158$, $p < 0.05$] revealed that although the first fixation duration was shorter for 32-pixel characters than for 24-pixel characters both in Kai and Ming [$F_{(1,62)} =$ 36.515 and 75.596, $p = < 0.01$, respectively], the difference was larger in Ming than in Kai (Figure 5(a)). The interaction between character spacing and font type [$F_{(1,62)} = 7.542$, $p < 0.01$] indicated that the first fixation duration was shorter with larger than with smaller character spacing in Ming [$F_{(1,62)} = 18.785$, $p < 0.05$], but there was no difference in Kai (Figure 5(b)).

For gaze duration, a significant main effect was found in character size [$F_{(1,62)} = 31.326$, $p < 0.0001$]. Gaze duration was shorter for 32-pixel characters ($M = 237.922$ ms) than for 24-pixel characters ($M = 246.148$ ms). A significant interaction between character size and font type [$F_{(1,62)} = 4.078$, $p < 0.05$] further indicated that the difference in gaze duration between 32-pixel characters and 24-pixel characters in Ming [$F_{(1,62)} = 32.253$, $p < 0.01$] was larger than that in Kai [$F_{(1,62)} = 10.099$, $p < 0.01$] (Figure 6(a)). Moreover, the significant interaction between character spacing and font type [$F_{(1,62)} = 9.411$, $p < 0.005$] indicated that gaze duration was shorter with 1/4 character spacing than with 1/8 character spacing in Ming [$F_{(1,62)} = 12.097$, $p < 0.01$], but there was no difference in Kai. On the other hand, gaze duration

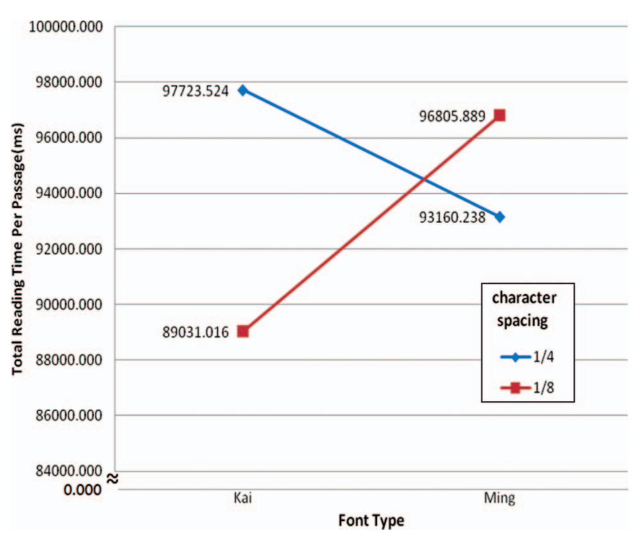

Figure 3. Interaction between character spacing and font type on total reading time per passage.

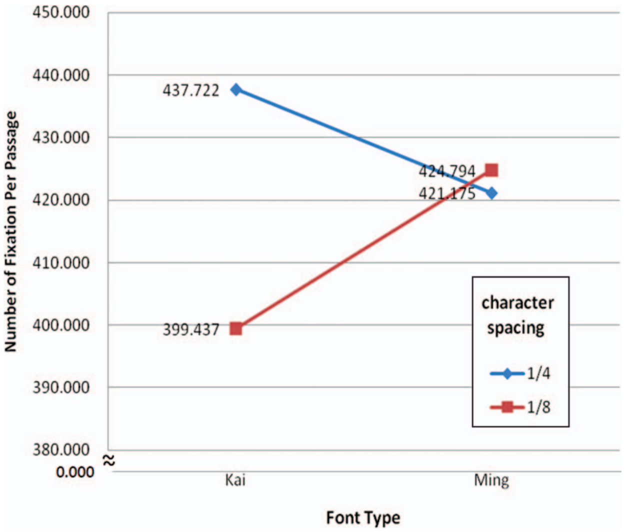

Figure 4. Interaction between character spacing and font type on number of fixations.

was shorter in Ming than in Kai with 1/4 character spacing [$F_{(1,62)} = 4.463$, $p < 0.05$], but there was no difference with 1/8 character spacing (Figure 6(b)).

3.3. *Saccade length and regression rate*

Analysis of saccade length revealed significant main effects of character spacing and font type. Saccade length was longer with 1/8 character spacing ($M = 3.910$) than with 1/4 character spacing ($M = 3.775$) [$F_{(1,62)} = 15.968$, $p < 0.0001$], and in Ming ($M = 3.893$) than in Kai ($M = 3.793$) [$F_{(1,62)} = 5.218$, $p < 0.05$]. In terms of regression rate, a main effect of character size was found [$F_{(1,62)} = 51.462$, $p < 0.0001$]. The regression rate was larger for 32-pixel ($M = 0.140$) characters than for 24-pixel characters ($M = 0.124$). With larger characters, participants were more likely to look back to previously read text than with smaller characters.

3.4. *Preference rating and comprehension score*

For preference rating, a significant main effect of character size [$F_{(1,63)} = 10.903$, $p < 0.005$] showed that readers preferred larger characters ($M = 4.094$) to smaller characters ($M = 3.785$). Moreover, there is a significant interaction between character size and font type [$F_{(1,63)} = 9.803$, $p < 0.005$]. Thirty-two-pixel characters were rated significantly superior to 24-pixel characters in Kai [$F_{(1,63)} = 22.340$, $p < 0.01$], and characters in Kai were preferred over those in Ming for 32-pixel characters [$F_{(1,63)} = 8.519$, $p < 0.01$]

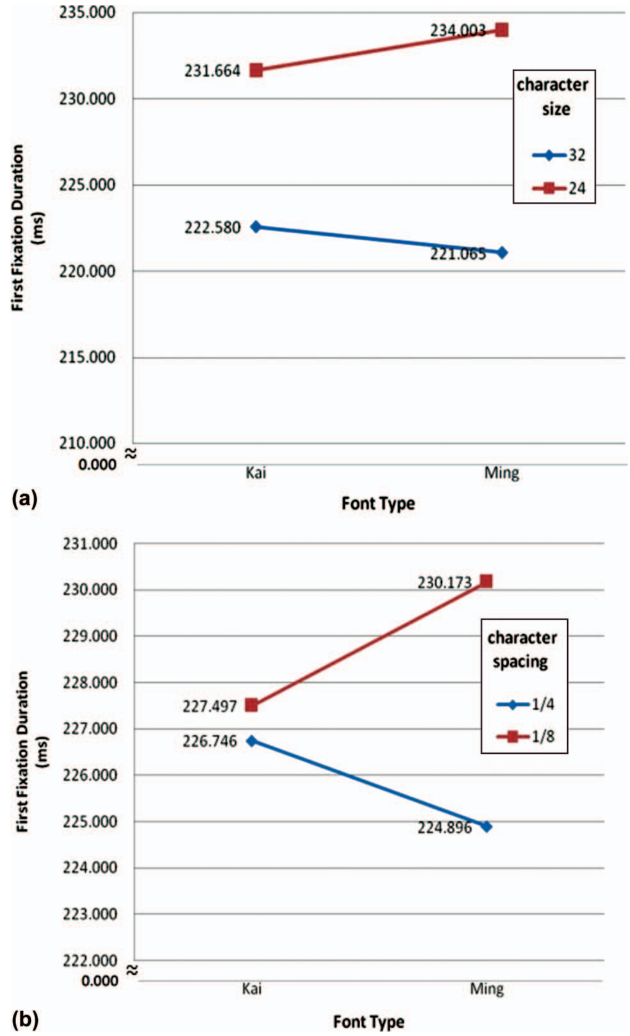

Figure 5. Interaction effects on first fixation duration. (a) Interaction between character size and font type. (b) Interaction between character spacing and font type.

(Figure 7). None of the effects was significant for the comprehension score.

4. Discussion

Results on the comprehension score showed that participants were able to comprehend all the passages well regardless of the different typographic conditions. With the same comprehension level, reading efficiency can be interpreted by overall reading time and eye-movement indicators without confounding. It is found that the reading speed for Chinese characters of Kai style in 24 pixels with 1/8 character spacing was the shortest. Character size significantly affected overall reading speed; specifically, text in 24-pixel characters was read faster than text in 32-pixel characters. Further eye-movement analyses revealed that text in smaller-sized characters had longer fixation duration,

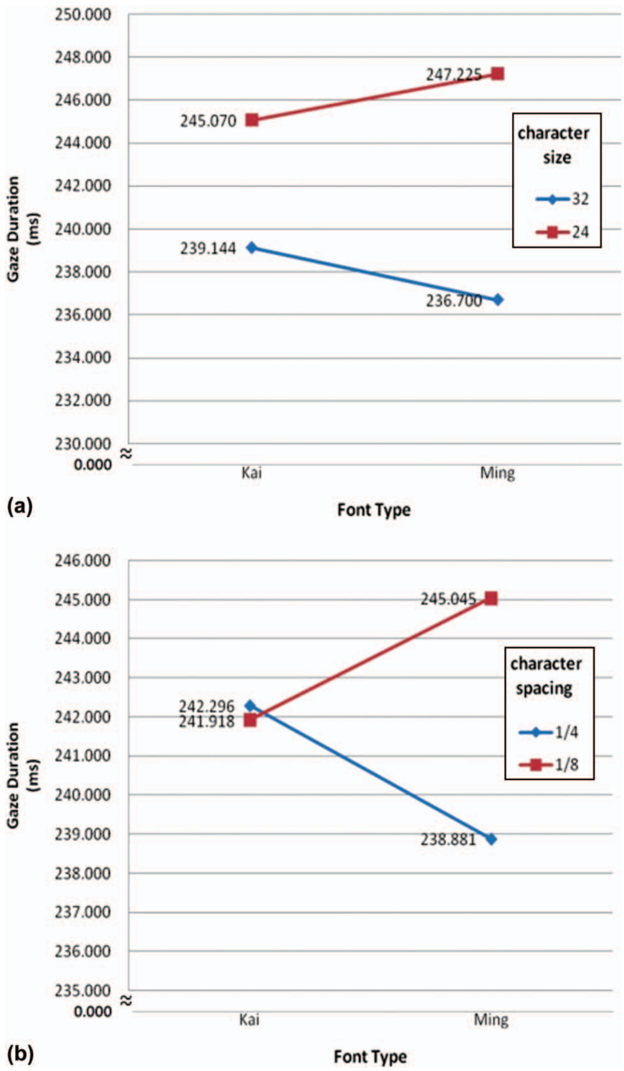

Figure 6. The interaction effects on gaze duration. (a) Interaction between character size and font type. (b) Interaction between character spacing and font type.

fewer fixations and fewer regressions than text in larger-sized characters. Therefore, the passages with smaller (41′ arc) character size produced better performance than larger (60′ arc) character size as expected. However, although the Ming type is more legible than Kai, it is not necessarily read faster. The interaction between character spacing and font type was observed on overall reading time and on some eye-movement measures. Generally, characters in Kai font were easier to read with 1/8 character spacing than with 1/4 character spacing as expected too. In the following sections, the effects of three typographic variables on overall reading efficiency will be discussed first. Then, the relationship between eye-movement measures and overall reading efficiency will be further discussed.

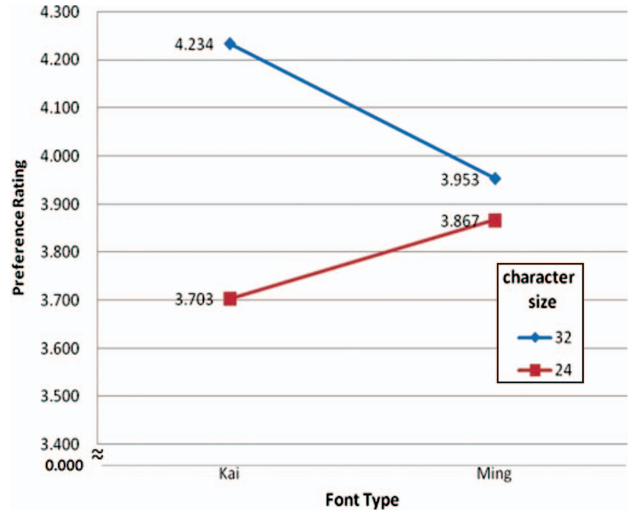

Figure 7. Interaction between character size and font type on preference rating.

4.1. *Overall reading efficiency*

The overall reading efficiency is reflected by the total reading time of a passage. Overall, among the eight combination conditions, the reading speed for Chinese characters of Kai type in 24 pixels with 1/8 character spacing was the shortest. Further analyses revealed that text in 24-pixel characters was read faster than text in 32-pixel characters. As mentioned before, the 24- and 32-pixel character sizes equal to 41′ and 60′ arc. Both are larger than the minimal recommended character size (33′ arc) (Wu *et al.* 2006). Moreover, the larger one is significantly larger than the minimal recommended character size. It is expected that the passages with 41′ arc character size produce better performance than those with 60′ arc if there is an optimal size for reading. The results found in the present study supported the hypothesis. Furthermore, Chan and Lee (2005) used 10- and 14-pt font sizes (equal to 27′ and 38′ arc, respectively) and found that passages with larger-size characters were read faster and comprehended better than those with smaller-size characters. According to the findings of Chan and Lee (2005) and the present study, there indeed exists an optimal size for reading Chinese characters. Characters that are too small or too large may decrease reading efficiency.

The effect of font type in the present readability task is different from those found in previous legibility studies. With the assessment of the legibility threshold of Chinese characters, it is usually found that Ming was more legible than Kai (Shieh *et al.* 1997, Cai *et al.* 2001). These results are reasonable because the Kai characters are smaller than those in

Ming type with the same font size (Cai *et al.* 2001). Cai *et al.* (2001) found that the Ming characters had larger height (9.59%), width (9.70%) and area (21.29%) compared with the Kai characters in their study. The material in the present study was also analysed, and the results again showed that the Ming characters are larger in height (11.38%), width (11.37%) and area (24.59%) than the Kai characters. With the same font size, larger characters are more legible than smaller characters.

However, we did not find any significant difference between Ming and Kai types on reading speed, which was the same as those observed in Wang and Chen (2003). The interaction between character spacing and font type found in the present study provides a good explanation why the story is different in a readability task. The interaction between character spacing and font type indicated that characters in Kai were easier to read with 1/8 character spacing than with 1/4 character spacing, or characters with 1/8 character spacing were easier to read in Kai than in Ming. This is expected because the Kai characters are thinner and smaller than the Ming characters; therefore, smaller character spacing fits better with the Kai type. The interaction between character spacing and font type suggests that different character spacings should be considered for different font types to make reading more efficient.

4.2. Eye-movement measures

For the effects of character size, longer fixation duration, fewer fixations and lower regression rates were found for smaller-sized characters than for larger-sized characters; however, no difference was found on saccade length. Tinker (Paterson and Tinker 1947, Tinker and Paterson 1955, Tinker 1963) suggests that the increased fixation duration for smaller-sized characters may be caused by reduced character legibility, and the increased fixation number for larger-sized characters may be due to a smaller perceptual span. Tinker argued that more legible text allows readers a wider perceptual span, which requires fewer fixations and longer saccades. In the present study, text presented in 24-pixel characters, which resulted in fewer fixations and fewer regressions, seems to be easier to read than text in 32-pixel characters. The effect of character size on fixation duration was more like that on the traditional legibility tasks. That is, smaller characters with reduced character legibility take longer to process (e.g. Snyder and Taylor 1979).

However, one of the issues raised by some investigators is whether saccades are executed to traverse a certain amount of visual angle or a certain number of characters (Tinker 1963, Morrison and Rayner 1981, O'Regan 1981). O'Regan (1980) argued that the number of characters is the critical determinant of saccade length. In other words, saccades should scale up for larger characters. Morrison and Rayner (1981) manipulated character size by viewing distance and found that saccade length did not differ significantly as viewing distance increased. In the present study, the saccade length was not affected by the character size either, supporting O'Regan's argument that saccade length depends on the number of characters and not the visual angle of the character. However, the saccade length was affected by character spacing in the present study. The saccade length was longer with 1/8 character spacing than with 1/4 character spacing. This result suggests that the 'number of character' hypothesis proposed by O'Regan is not fully supported. Further research is needed to clarify this issue.

The interactions between character spacing and font type suggest that the effects of different character spacings are different in different font types. It is interesting to note that the interaction pattern of fixation number is consistent with the total reading time per passage, which is different from those of fixation durations. For total reading time and the number of fixations, the effects of character spacing were shown in Kai but not in the Ming type. However, for both first fixation duration and gaze duration, the effects of character spacing were pronounced in Ming but not in the Kai type. Overall, if we treat eye-movement measures as reflecting the detailed components in overall viewing time, the effects of typographic variables for overall reading efficiency can be more consistently shown by their effects on fixation number instead of their effects on fixation duration.

Since the effect of typographic variables on fixation duration seems to be different from that on other eye-movement measures, an issue worth further discussing is how typographic variables affected fixation duration. Typographic variables such as quality of the print and character size may influence fixation duration because of character legibility (Tinker 1963). Therefore, it is reasonable that increased fixation duration was found for smaller-sized characters and for smaller character spacing. In the present study, we further differentiated first fixation duration and gaze duration. The first fixation duration is a measure that reflects the relatively earlier stage of lexical access (Inhoff 1984). Since gaze duration is the summed duration of all fixations on the target character prior to any movement away from the target character, the first fixation duration is part of the gaze duration. Observed effects on gaze duration, but not on first fixation duration, may reflect the influence of delayed or integrative reading processes (Just and Carpenter 1980). It was found that the effects of typographic variables on the first fixation duration and the gaze duration are quite similar, which suggests that typographic variables have more influence on the earlier rather than on later integrative processes. Since the fixation duration reflects the effects of typographic variables on early information process such as character legibility or lexical access, its effects may be more like those on the legibility tasks. This hypothesis can be examined with more eye-movement studies on readability tasks in the future.

4.3. Relationship between subjective preference and performance

Participants' preference ratings indicated that they preferred to read larger-sized characters than smaller-sized characters. Although the first fixation duration has the same pattern as preference rating, the total reading time, fixation number and regression rate show the opposite pattern. Further analysis even showed that the character size effect on preference rating was especially prominent in the Kai style but not in the Ming style. None of the overall reading speed or eye-movement measures revealed this pattern. All these results suggest that the subjective preference does not necessarily correspond to reading performance. Other studies in Chinese (e.g. Shieh *et al*. 1997) also found that subjective preference did not correspond to objective measures either. Therefore, when designing the most efficient way to represent text in reading Chinese on computer displays, one should consider the results from objective measures in addition to the subjective preference.

5. Conclusion

Generally speaking, Chinese characters in Kai font in 24 pixels with 1/8 character spacing had the shortest reading speed. The analyses of eye movements provide more detailed information about how typographic variables affect readers' reading efficiency. Reading text in smaller-sized characters had longer fixation duration, fewer fixations and fewer regressions than text in larger-sized characters. However, there is an optimal size for reading Chinese characters, which may lead to best reading performance. Furthermore, interaction between character spacing and font type was observed on overall reading efficiency and on eye-movement indicators, which suggests that different character spacings should be considered in different font types to make reading more efficient. Therefore, the findings in the present study do provide some useful design recommendations for screen display format and layout to improve reading performance in Chinese. Further studies are needed to examine how other font types (e.g. Hei and Li), other typographic variables (e.g. line spacing, contrast, illumination, etc.), and different combination of different typographic variables may affect reading performance and eye-movement patterns. Moreover, eye-movement techniques such as moving window technique could be applied to the studies of typographic variables to examine how different typographic variables affect the perceptual span.

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