Effect of pattern complexity on the visual span for Chinese and alphabet characters

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The visual span for reading is the number of letters that can be recognized without moving the eyes and is hypothesized to impose a sensory limitation on reading speed. Factors affecting the size of the visual span have been studied using alphabet letters. There may be common constraints applying to recognition of other scripts. The aim of this study was to extend the concept of the visual span to Chinese characters and to examine the effect of the greater complexity of these characters. We measured visual spans for Chinese characters and alphabet letters in the central vision of bilingual subjects. Perimetric complexity was used as a metric to quantify the pattern complexity of binary character images. The visual span tests were conducted with four sets of stimuli differing in complexity—lowercase alphabet letters and three groups of Chinese characters. We found that the size of visual spans decreased with increasing complexity, ranging from 10.5 characters for alphabet letters to 4.5 characters for the most complex Chinese characters studied. A decomposition analysis revealed that crowding was the dominant factor limiting the size of the visual span, and the amount of crowding increased with complexity. Errors in the spatial arrangement of characters (mislocations) had a secondary effect. We conclude that pattern complexity has a major effect on the size of the visual span, mediated in large part by crowding. Measuring the visual span for Chinese characters is likely to have high relevance to understanding visual constraints on Chinese reading performance.

Introduction

English text is read with a series of eye fixations separated by saccades. On each fixation, only a small number of letters can be recognized with high accuracy. The concept of visual span captures this limitation and appears to be an important sensory factor limiting reading speed in normal and low vision (Cheong, Legge, Lawrence, Cheung, & Ruff, 2008; Legge et al., 2007). In this paper, we extend the concept of visual span to Chinese characters and examine how the greater pattern complexity affects the visual span.

First introduced by O'Regan (1990) and O'Regan, Levy-Schoen, and Jacobs (1983), the visual span can be defined as the number of adjacent letters, formatted as in text, that can be recognized reliably without moving the eyes. The visual span in normal central vision includes approximately 10 letters (Fine & Rubin, 1999; Legge et al., 1997; Legge, Mansfield, & Chung, 2001; Rayner & Bertera, 1979). Legge et al. (2001) developed a method for measuring the visual span that was intended to isolate constraints on pattern recognition from oculomotor and contextual influences (Figure 1). A trigram composed of three random letters side by side is presented on a horizontal line at different eccentricities indicated by the position of the middle letter. A visual span profile is a plot of the letter-recognition accuracy (proportion correct) versus the letter position.

The concept of visual span has been primarily studied for alphabet letters. But it is likely that the underlying sensory constraints apply to patterns in

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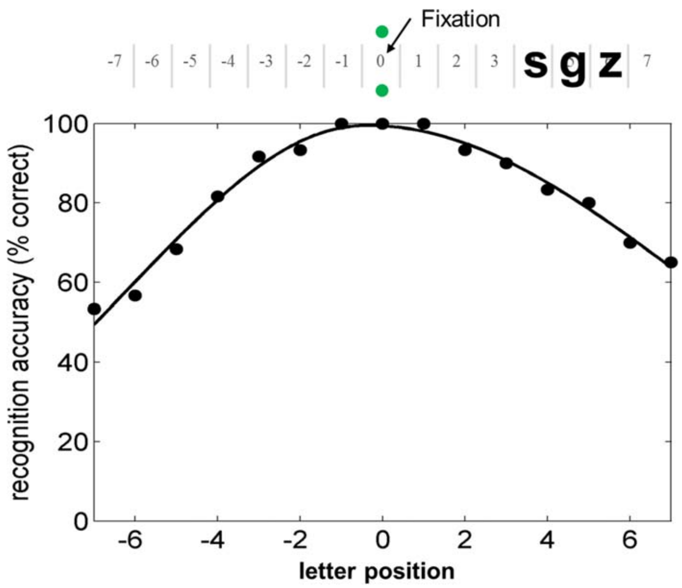

Figure 1. The visual span test for alphabet letters using the trigram method. Top: Schematic illustration of a trigram trial. A string of three randomly selected letters is presented for 250 ms at a position left or right of fixation. Fixation is maintained between the two green dots. The subject is asked to identify the three letters from left to right. Bottom: The visual-span profile is a plot of recognition accuracy (% correct) versus letter position based on a block of trigram trials.

other scripts. We are interested in extending the concept of visual span to Chinese characters for three reasons: to verify that a similar constraint applies, to examine the impact of the greater pattern complexity of Chinese characters, and to confirm the likely relevance to Chinese reading performance.

Pattern complexity varies, even among the most frequent Chinese characters. The most commonly used measure of complexity in Chinese characters is to count the number of strokes. There have been several proposed measures of complexity for alphabet letters. Bernard and Chung (2011) used the length of the skeleton (i.e., total stroke length) to quantify the complexity of alphabet letters in different fonts. Majaj, Pelli, Kurshan, and Palomares (2002) developed a stroke frequency measure that is the number of intersections formed by horizontal lines across the character divided by the width of the character. Considering the common occurrence of horizontal and vertical strokes in Chinese characters, Zhang, Zhang, Xue, Liu, and Yu (2007) modified Majaj et al.'s definition by using slices horizontally, vertically, and diagonally oriented across the character and computed the stroke frequency as the maximum number of intersections among all the slicing directions. Another metric is the perimetric complexity, which is defined as the perimeter squared of a symbol, divided by the "ink" area (Arnoult & Attneave, 1956; Pelli, Burns, Farell, & Moore-Page, 2006). One of our objectives was to quantify the pattern complexity of Chinese characters and alphabet letters and investigate the effect of complexity on the size of the visual span. We considered four metrics for complexity measures, including stroke count, ink density, stroke frequency, and perimetric complexity. Cross-correlation analysis indicated that the measures are highly correlated, and especially the perimetric complexity showed relatively high correlations with all other methods and can be applied for both alphabet and Chinese characters. The detailed analysis of pattern complexity and criteria for selecting the stimulus sets are provided in Appendix A.

We are also interested in the sensory factors limiting the visual span and how they are altered by pattern complexity. Three factors have been proposed to account for the size of the visual span—decreased letter acuity away from fixation, increased crowding between adjacent letters, and decreased accuracy for the ordering of letters within a string (referred to as mislocations) (Legge et al., 2007). Findings from Pelli et al. (2007) and from our lab (He, Legge, & Yu, 2013) indicate that crowding plays a major role in limiting the size of the visual span for alphabet letters. If that is true more generally, we should expect to see a strong relationship between the size of the visual span and crowding in both alphabet letters and Chinese characters. In this paper, we report on a decomposition analysis to evaluate the contributions of acuity, crowding, and mislocations in limiting the visual spans for alphabet and Chinese characters.

The visual span hypothesis proposes that the size of the visual span imposes a sensory bottleneck for reading speed. Studying the visual span for Chinese characters may set the stage for a future test of this hypothesis for Chinese reading.

To summarize, the main objective of this paper is to investigate how pattern complexity alters the visual span in Chinese and alphabet characters. In addition, we apply a decomposition analysis to evaluate the contributions of acuity limitation, crowding, and mislocations to the size of the visual span in both scripts.

Methods

Subjects

Twelve bilingual college students (six males and six females) with normal or corrected-to-normal vision participated in the experiments. They were all native Chinese speakers with over 10 years' experience in English. The subjects signed an Internal Review Board (IRB) approved consent form before the experiments.

Group	Mean	*SD*	Min	Max
LL	48.6	11.7	30.1	75.4
UL	66.5	17.9	34.4	111.4
C1	98.0	6.3	85.8	105.9
C2	136.9	2.3	132.7	140.7
C3	176.6	4.3	169.6	183.6
C4	216.2	5.0	209.1	224.5
C5	280.1	33.7	250.9	415.2

Table 1. Statistical summary of perimetric complexity values for each complexity group ($n = 26$).

Stimuli

Perimetric complexity (Pelli et al., 2006) was used to quantify the complexity for all the symbols. Lowercase (LL) and uppercase (UL) alphabet letters (Arial font) comprised two sets of 26 symbols with lowest complexities. Seven hundred of the most frequently used Chinese characters (Heiti font, which has the same width for all the strokes of a character) were identified from an official character frequency table (State Language Work Committee, Bureau of Standard, 1992) and divided into five nonoverlapping groups based on even separations of the complexity values. The complexity range found in the most frequent 700 characters covers most of the range of complexity across all simplified Chinese characters. Simplified Chinese characters are standardized for use in Mainland China and were created by decreasing the number of strokes in the traditional characters, which are still used in Hong Kong, Macau, and Taiwan. Remaining characters with even higher complexity are rarely used in ordinary texts. Twenty-six characters with medium complexity values were selected from each complexity group to form a set of symbols (C1–C5) with the same number of characters as the LL and UL groups. Characters with very high or low similarity were excluded from the stimulus sets (see Appendix A for the definition of the similarity measure). Statistics of the perimetric complexity values for each stimulus set are given in Table 1. Groups LL, C1, C3, and C5 were used for visual-span testing (Figure 2). For these groups, the complexity scores have no overlap.

Each stimulus character was stored as a binary image with tightly fit boundaries to include all the strokes. The size of the stimuli (height in Chinese characters and x height in alphabet letters) subtended 1° retinal angle at a viewing distance of 40 cm. According to Zhang, Zhang, Xue, Liu, and Yu (2009), this character size is well above acuity threshold (over six times larger) in central vision for all complexity groups.

Stimuli were presented on a Sony monitor (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1280 × 960). The characters were displayed as dark stimuli on a white background (50 cd/m^2). The correspondence between gray level and luminance was calibrated with a Spyder calibrator. The experiment was controlled in Matlab 5.2.1 with Psychophysics Toolbox extensions.

Procedure

The visual span was measured using three methods. Experiment 1 involving recognition of trigrams with full report was the main experiment, which extended measurements of visual span from alphabet letters to include the three sets of 26 Chinese characters. Two additional experiments (Experiments 2 and 3) were conducted to examine the sensory and cognitive factors limiting the visual span, one involving the recognition of single characters and the other involving trigram presentation with partial report.

Six subjects participated in the trigram test with full report. Each trigram consisted of three characters randomly drawn from the set of 26 characters in a given complexity group and presented side by side at varying distances from fixation (Figure 1). There were 17 positions on a horizontal line through central fixation, from −8 (left) to 8 (right) with respect to the midline position (designated zero). Center-to-center spacing between adjacent slots is 1 × width (= 1° retinal angle). In each block, there were 85 trials for trigrams centered at each of the 17 positions, presented in a randomized order. There were four blocks per session, one for each of the complexity groups. The experiment consisted of four sessions of repeated tests, with a total of 1,360 trials. The order of complexity was counter-balanced between sessions and subjects.

At the beginning of each block, the subject was shown the 26 symbols to be tested on a hard copy page and urged to restrict responses to the stimulus set. For each trial, two vertically aligned green dots appeared at

LL	C1	C3	C5
a b c d e f g	不 大 上 下 之 公 小	的 有 他 和 说 经 民	就 着 高 重 意 最 题
h i j k l m n	力 从 么 又 水 二 今	进 者 种 定 所 利 电	量 德 调 真 望 精 赛
o p q r s t u	儿 认 少 才 众 九 土	把 总 点 使 很 金 话	影 整 需 境 断 随 富
v w x y z	乡 火 六 飞 七	界 战 拉 统 身	黑 镇 愿 拿 喜

Figure 2. Stimulus sets for the visual span test. Pattern complexity increases between panels from left to right.

the center of the screen. The subject was directed to fixate between the two dots during presentation of the stimulus trigram. The stimulus lasted for 250 ms on the screen. After that, the screen became blank and the subject was asked to report the three characters of the trigram in left-to-right order. The reference page was available when the subject failed to recall the characters in the stimulus set. The frequency of out-of-set report was very rare (<1% of the total trials). The experimenter recorded the responses, and the subject triggered the mouse to start the next trial. Eye movements were monitored during stimulus presentations with a camera set on top of the display screen. A trial was excluded if an eye movement was observed by the experimenter or reported by the subject; however, the occurrence of eye movements was very rare (less than 10 trials per subject). A practice session was included before the formal test to ensure that the subject could fixate stably during stimulus presentation.

Six subjects participated in Experiment 2. The design of Experiment 2 was the same as Experiment 1 except that single characters, rather than trigrams, were presented on each trial. The subject simply reported the character. Like Experiment 1, complexity was varied in four blocks per session and four sessions. The purpose of this experiment was to evaluate the effects of acuity limitations on the visual span.

Six subjects (the same group as Experiment 2) participated in Experiment 3. The trigram stimuli in Experiment 3 were the same as Experiment 1. But instead of responding to all three stimuli (full report), the subject was only required to report one of the three characters in a given trial (partial report). The left, middle, and right characters in the trigram were tested in separate blocks, and the subject was informed about the position to be reported before start of a new block. One session consisted of 12 blocks (4 Complexity Groups $\times$ 3 Within-Trigram Locations). We expected the partial-report procedure to reduce memory load and to direct spatial attention to a specific character in the trigram. If the influence of complexity on the visual span (Experiment 1) was due to these higher level factors, we expected that the results from the partial-report experiment would reveal a weaker complexity effect.

Data analysis

Visual span profile and visual span size

The accuracy of character recognition was plotted as a function of symbol position, from -7 to $+7$, to create a visual-span profile for a given complexity group (see Figure 1 for an example). (Positions ± 8 were not included because the absence of trigram stimuli at $\pm$ 9 meant fewer stimuli tested at ± 8.) The profiles for Experiment 1 (full report) were fitted by the sum of two Gaussians with six parameters: the amplitudes, the means, and the standard deviations of the two Gaussians. The profiles in Experiment 3 (partial report) were fitted by split Gaussians with four parameters: the amplitude, the mean, and the standard deviations of the left and right sides. This difference in curve-fitting procedure was based on inspection of the adequacy of the fits. For both full and partial reports, the visual span size was computed as the width of the fitted profile curve (number of characters included) at a criterion of 80% correct. A one-way repeated measures analysis of variance (ANOVA) test was performed to investigate the effect of complexity on the size of the visual span.

Visual span decomposition

The contribution of sensory limitations to the visual span was quantitatively assessed by estimates of losses of character information due to decrease in acuity away from the midline, crowding, and character mislocation. A detailed description of the decomposition approach can be found in He, Legge, and Yu (2013). In brief, three types of visual span profiles were plotted: a conventional profile based on correct recognition of the character and its position in the trigram with full report, a profile allowing for mislocations, i.e., a character was counted as correct if properly identified but reported out of order in the trigram, and a profile based on recognition of isolated characters. The effect of acuity limitation was calculated by the area between 100% correct and the isolated character profile. Quantification of crowding was defined by the area between the curves of isolated character and trigram identification allowing mislocation errors. The contribution of mislocation was assessed by the area between curves with and without allowing the mislocation errors. The summation area was then transformed to the number of bits loss. The conversion is based on an information-theory measure for the size of the visual span, where 100% accuracy in recognizing one of the 26 characters is equivalent to 4.7 bits (Legge et al., 2001). Two-way (Decomposition Factors $\times$ Complexity) repeated-measures ANOVA were conducted to examine the effect of the sensory factors in each of the complexity groups.

Results

Experiment 1: Visual span for trigrams with full report

Visual span profiles for trigrams with full report are shown in Figure 3A for each of the complexity groups. The profiles all have qualitatively similar shapes. Mean

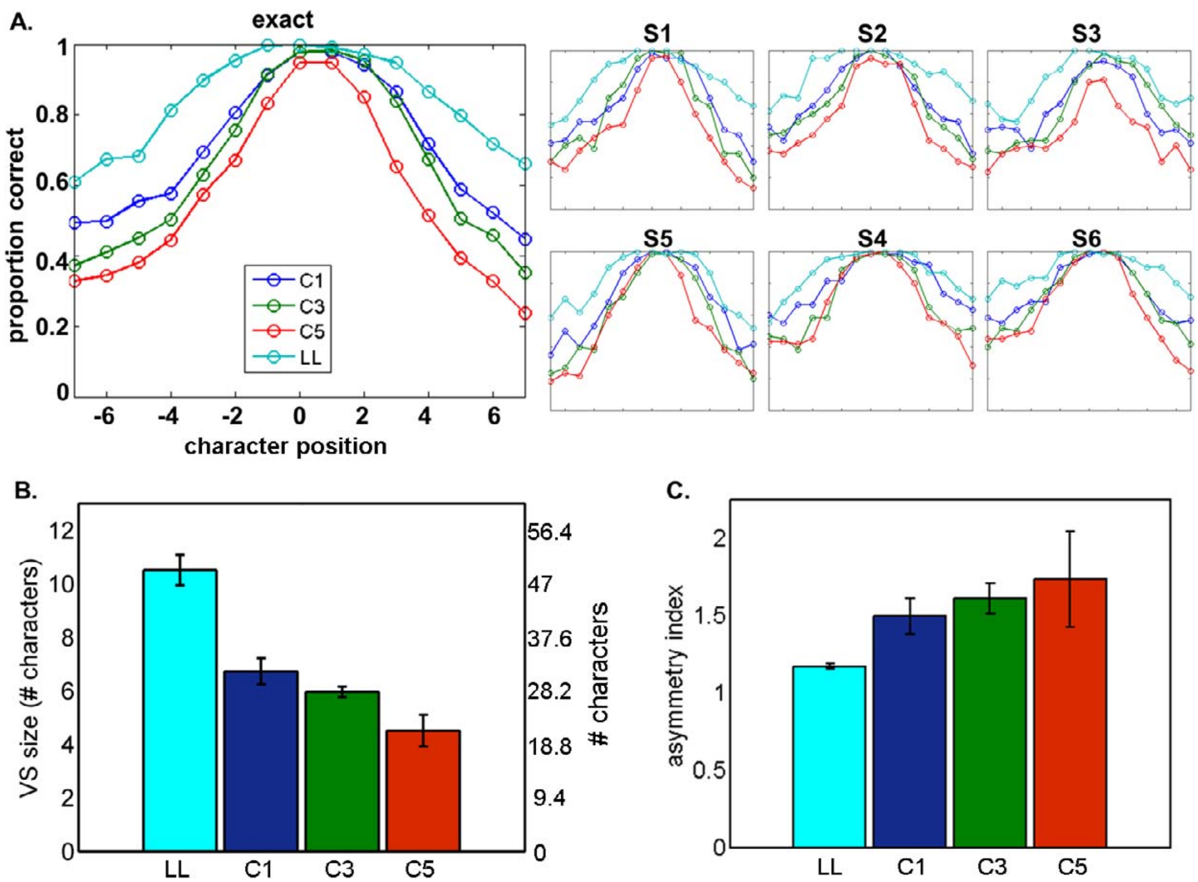

Figure 3. Visual spans for four levels of complexity—lowercase alphabet letters (LL) and three groups of Chinese characters (C1, C3, and C5)—in trigram recognition with full report. A. The visual span profiles are plotted as a function of response accuracy against test position. Fifteen locations (between −7 and +7) were included in the plots. Left: the average performance of six subjects (S1–S6), right: individual data from each subject. B. The size of the visual span (number of characters) for each complexity group was calculated for an accuracy criterion of 80% correct. C. The asymmetry index of visual span for each complexity group. Error bars: ±1 *SE*.

recognition accuracy across subjects approached 100% correct at the fixation for all the complexities and systematically dropped with increasing distance from fixation. However, the visual-span profiles get narrower as complexity increases. In other words, recognition performance decreases more rapidly away from the midline as complexity increases. Individual data mostly complied with the average performance. For S3, response accuracy was noticeably below 100% correct at Position 0 for Groups C1 and C5 (especially during the first two sessions of the test).

We defined the size of the visual span as the width of the profile at an accuracy criterion of 80% correct for each complexity. The results are shown in Figure 3B and Table 2. The size of the visual span systematically decreased with complexity, from 10.5 letters for LL to 4.5 characters for C5 (Figure 3B). A one-way repeated measures ANOVA showed that complexity had a significant effect on the visual span, $F(3, 20) = 28.2$, $p < 0.001$). Pairwise comparison between the complexity groups indicated that the visual span size for LL (10.5 characters) was significantly greater than each of the three Chinese groups, and the size for C1 is significantly greater than C5 (4.5 characters), but the size for C3 (6.0 characters) did not differ significantly from C1 or C5.

The visual span profiles have slightly asymmetric shapes, broader to the right of fixation. We computed

	Full report		
	Exact[1]	Allowing mislocation[2]	Partial report
LL	10.5 ± 0.56	11.5 ± 0.67	12.1 ± 0.69
C1	6.7 ± 0.48	8.2 ± 0.60	9.6 ± 0.36
C3	6.0 ± 0.20	7.1 ± 0.29	8.5 ± 0.50
C5	4.5 ± 0.58	5.7 ± 0.48	7.5 ± 0.47

Table 2. Visual span size in number of characters (mean ± *SE*) for trigram recognition with full and partial reports. *Notes*: [1]Exact: recognition requiring trigram characters to be reported in the correct order; [2]allowing mislocation: recognition without requiring trigram characters to be reported in the correct order.

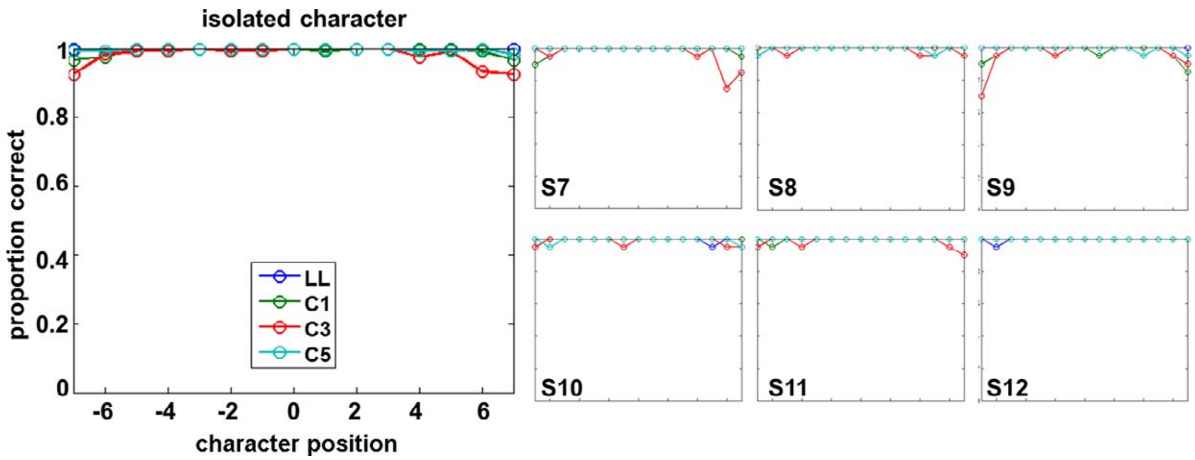

Figure 4. Visual span profiles for isolated characters in the four complexity groups. Recognition accuracy of group mean (S7–S12) (A) and individual subjects (B) are plotted as a function of test position. Fifteen locations (between −7 and +7) are included in the profiles.

an asymmetry index as the ratio of the right-side breath to the left at the criterion of 80% correct. Data from subject S3 was excluded because all points on the visual span profile to the left of fixation for C5 were below the 80% criterion. Figure 3C shows that the asymmetry index was consistently greater than one for all the complexity groups, with more asymmetry in Chinese characters than alphabet letters. However, a one-way repeated measures ANOVA indicated that the asymmetry indices were not significantly different between complexity groups, $F(3, 16) = 1.95$, $p = 0.16$. The asymmetry of visual span profiles for alphabet letters has been shown previously. Legge et al. (2001) reported an asymmetry ratio of 1.3 in native English speakers by computing the ratio of standard deviations (right/left) of the split Gaussian fits to visual-span profiles.

To assess the impact of mislocations on the visual-span profiles, we computed recognition accuracy without requiring trigram characters to be reported in the correct order. The profile shapes were similar to the standard profiles, but somewhat broader. Using the same criterion of 80% correct, the visual span size was estimated for each complexity group. The quantitative results are summarized in Table 2. The size difference between exact scoring and allowing mislocations reveals that mislocation errors lead to one to 1.5 character shrinkage of the visual span across complexities, which accounted for approximately 10% reduction in the size of the visual-span profile for LL and 20% for C5.

A one-way repeated-measures ANOVA was conducted to examine the complexity effect on the visual-span size with mislocations and showed that the sizes were significantly different among the complexity groups, $F(3, 20) = 22.0$, $p < 0.001$. Pairwise comparisons generated similar results as shown in the previous analysis: the size for LL (11.5 characters) was significantly greater than all the Chinese character groups and size for C1 (8.2 characters) was significantly greater than C5 (5.7 characters), but the size for C3 (7.1 characters) did not significantly differ from C1 or C5.

Comparison of the first two columns in Table 2 indicate that mislocations have an impact on the size of the visual span. But even when mislocations are not counted as errors, the size of the visual span decreases with increasing complexity.

Experiment 2: Visual span for isolated characters

To examine the effect of acuity on visual-span profiles, we plotted recognition accuracy for isolated characters in the four complexity groups as a function of position (Figure 4). At all complexity levels, response accuracy remained well above the 80% correct level across the test positions. Performance was close to 100% correct until ±6 slots away from fixation and then started to drop a little in groups C3 and C5. These results indicate that acuity has little impact on the shape of visual span profiles for Chinese as well as alphabet characters.

Visual span decomposition

The decomposition analysis separated the contributions of reduced acuity, crowding, and mislocations in limiting the size of the visual span. The information losses due to these three factors are shown in Figure 5. Crowding is the dominant factor limiting the visual span for all the complexity groups. The effect dramatically increases with complexity, from 8.9 bits for LL to 22.3 bits for C5. Mislocation plays a

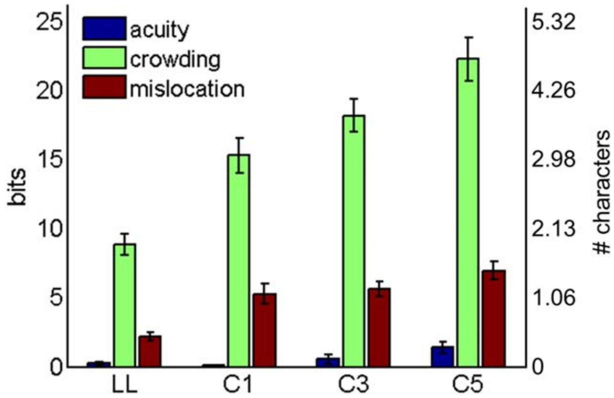

Figure 5. Visual span decomposition. The impact of acuity, crowding, and mislocations on the visual span were examined separately through a decomposition analysis. The magnitudes of the three factors were plotted as information losses (in bits) relative to perfect performance summed across the character positions tested. Results are shown for the four complexity groups (LL, C1, C3, and C5). Error bars: ±1 *SE*.

secondary role. The amount of information loss due to mislocations was greater in the Chinese character groups than the alphabetic group. Decreasing acuity away from the midline has very little impact.

A 3 × 4 (Decomposition Factors [Acuity, Crowding, Mislocations] × Complexity [LL, C1, C3, C5]) two-way repeated-measures ANOVA was conducted to inspect impact of the sensory factors and the complexity groups. The result showed that there was a significant main effect of the sensory factors on the amount of information loss, $F(2, 60) = 398$, $p \approx 0$. The pairwise comparison indicated that for all the complexity groups, the impact of crowding (8.9 bits for LL, 15.3 bits for C1, 18.2 bits for C3, and 22.3 bits for C5) was significantly greater than that of degraded acuity (0.2 bits for LL, 0.1 bits for C1, 0.5 bits for C3, and 1.4 bits for C5) or mislocation (2.2 bits for LL, 5.3 bits for C1, 5.6 bits for C3, and 7.0 bits for C5), and the effect of mislocation was significantly greater than the acuity limitation. In addition, there was a significant interaction between the sensory factors and the complexity, $F(6, 60) = 11.1$, $p < 0.001$.

Experiment 3: Visual span for trigrams with partial report

To assess the impact of some higher level factors beyond early sensory encoding, we compared visual-span profiles measured with partial report with the standard visual spans. In the partial report procedure, subjects were required to report only one letter of a trigram on each trial (see Methods, Experiment 3). The visual span profiles with partial report (Figure 6A) are broader, but have qualitatively similar shapes to those with full report (Figure 3A). Once again, the profiles decrease in size with increasing complexity. This dependence on complexity implies that the high-level cognitive factors associated with responding to three items rather than one do not by themselves account for the impact of complexity in our study. Using the criterion of 80% correct, the estimated visual span sizes are shown in Figure 6B. The quantitative results are summarized in Table 2. The sizes with partial report are all larger than those with full report—about 1.6 characters for alphabet letters and from 2.5 to 3 characters for Chinese characters.

A one-way repeated-measures ANOVA showed that complexity has a major effect on the visual-span size with partial report, $F(3, 20) = 14.1$, $p < 0.001$. Pairwise comparison revealed similar results to the full report. The visual-span size for LL (12.1 characters) was significantly greater than the Chinese character groups, and the size for C1 (9.6 characters) was significantly greater than C5 (7.5 characters), but there was no significant difference between C3 (8.5 characters) and C1 or C5.

Although the results described here average across characters in the three positions within trigrams, the visual spans can be divided into the outer (farthest from the fixation), middle, and inner (nearest to the fixation) positions in trigrams to examine the variations among flankers and target. The details of such analyses are provided in Appendix B.

Discussion

The goal of our study was to extend the concept of visual span from alphabet letters to Chinese characters and to examine the impact of pattern complexity. We found similar shapes of visual-span profiles for alphabet letters and Chinese characters, suggesting that common constraints may apply to the recognition of different scripts. The visual-span size of 10.5 for lowercase alphabet characters, obtained in this study with bilingual native-Chinese speakers, is consistent with results for native English speakers. Legge et al. (2001) reported that the size of the visual span was ∼ 11 letters for a stimulus presentation time of 200 ms and a criterion of 80% correct in central vision. This agreement across subjects with different native languages is consistent with a sensory basis for determinants of the size of the visual span.

We asked how pattern complexity would affect the size of the visual span and found a systematic shrinkage of the visual span with increasing perimetric complexity. The size of the visual span decreased by six characters from alphabet letters (LL) to the most complex Chinese characters (C5) and decreased by 2.2

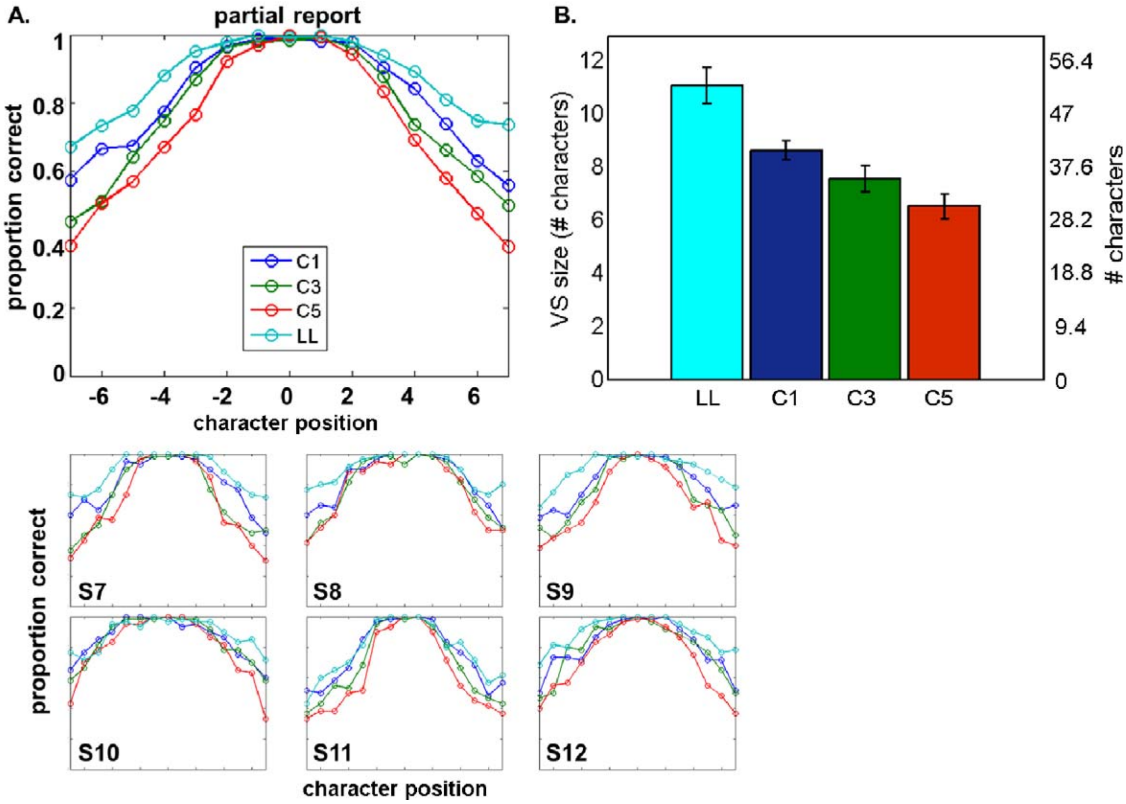

Figure 6. Visual spans for the four complexity groups (LL, C1, C3, and C5) in trigram recognition with partial report. A. The visual span profiles are plotted as response accuracy against test position. Fifteen locations (between −7 and +7) are included. Top: the average performance of six subjects (S7–S12), bottom: individual data from each subject. B. The size of the visual span (number of characters) in partial report is shown for the accuracy criterion of 80% correct for each complexity group. Error bars: ±1 *SE*.

characters from the simplest to the most complex Chinese group. These results imply that pattern complexity is a physical stimulus property that affects the size of the visual span.

The perimetric complexity metric (Attneave & Arnoult, 1956) has been used to study symbol recognition. Pelli et al. (2006) studied character recognition for a wide range of alphabets, scripts, and words, and reported a negative linear relationship between statistical efficiency for recognition and pattern complexity. Pelli et al. argued that perimetric complexity provides an objective measure that physically describes the visual patterns and can be used to predict the efficiency for symbol identification. The results of our experiments demonstrate that perimetric complexity is also useful in determining the visual span for sets of different scripts.

We considered whether the higher error rates in the more complex groups might be due to particular difficulty with a small number of characters. For this purpose, we looked at the frequency of recognition errors in the full-report data for the 26 characters in each complexity group. There was only one outlier found in the alphabet letter group (the letter k), but none in the Chinese character groups. We conclude that the higher error rates in the more complex groups were not due to a few unusually difficult characters in the stimulus sets.

A concept related to the visual span is the "perceptual span," which refers to the region of visual field that influences eye movements and fixation times in reading (McConkie & Rayner, 1975). The perceptual span for reading alphabetic text was estimated to extend 15 letters to the right of fixation and four to the left (McConkie & Rayner, 1975; Rayner, Well, & Pollatsek, 1980). Using a similar paradigm, Inhoff and Liu (1998) tested the perceptual span in Chinese text and reported much smaller numbers: three characters to the right and one to the left. To explain the discrepancy, the authors discussed the differences in linguistic processing during reading fixations for morphographic and alphabetic scripts. The difference in amount of visual information contained in one character was acknowledged without further investigation. The visual span test in our study eliminates the contextual influence and focuses more on the sensory process in recognizing strings of characters. It is likely that the differences we found in visual spans for alphabet and Chinese characters played a role in the large difference in perceptual spans reported by Inhoff and Liu (1998).

We were further interested in the sensory factors that contribute to the reduced visual span with complexity. The reduction cannot be explained by acuity limitation. Performance for isolated characters is close to the ceiling across all the complexity groups. This observation is consistent with Zhang et al. (2009) who showed that the acuity limit for the most complex Chinese characters at 10° was close to 45 arcmin; our stimuli subtended 1° and extended less than 10° into the periphery. However, the lack of an acuity effect on visual span does not mean that acuity has no influence on complex symbol recognition in peripheral vision. Zhang et al. (2009) measured acuity thresholds for Chinese characters at six complexity levels and found that at 10° eccentricity, the threshold size almost doubled from simplest to the most complex characters. In addition, the authors reported a greater scaling factor from central to peripheral vision for more complex characters. In our study, the stimulus size was well above the acuity thresholds measured by Zhang et al. (2009). We conclude that acuity plays little role in limiting the visual span for both alphabet and Chinese characters.

Our decomposition analysis showed that crowding is the major factor limiting the visual span for all the complexity groups. This result extends the findings of Pelli et al. (2007), who demonstrated a strong link between visual span, crowding, and reading speed and argued that the visual span was primarily limited by crowding. We also found that the amount of crowding dramatically increases with complexity, which was the primary factor explaining the narrowing visual span profiles for more complex characters. The underlying mechanism of crowding has been explained by inappropriate feature integration (Pelli, Palomares, & Majaj, 2004). Following this proposal, increasing crowding should be associated with more scrambling of features. Balas, Nakano, and Rosenholtz (2009) proposed a model of "joint statistics by receptive cells" to explain feature integration. They argued that scrambled features were perceived under crowding due to the statistical combination of textural representations. In our study, when more interweaving strokes are present in complex characters, the possibility of getting scrambled representation of features in crowded characters becomes significantly greater. Therefore, we would expect more crowding for strings with more complex characters.

Bernard and Chung (2011) investigated the dependence of crowding on flanker complexity for four alphabet fonts with varied complexity (Times Roman, Courier, Edwardian, and Aristocrat). With a fixed center-to-center spacing of 0.8 x-height, they tested target letter recognition of a trigram in peripheral vision. They reported that the error rate increased with flanker complexity within simpler font groups (Times Roman and Courier) but approached a plateau in more complex fonts (Edwardian and Aristocrat). However, their data figures indicate an increasing average error rate across fonts, from the least complex Times Roman to the most complex Aristocrat, consistent with the complexity effect we observed.

The analysis of the visual span in this paper focused on recognition performance for characters as specific distances from fixation, averaged across cases when the character was in the middle, inner, and outer positions of a trigram. However, it is known that the outward letters are more recognizable than the inward letters in alphabet words (Bouma, 1973). Legge et al. (2001) separated their visual-span profiles into sub-profiles for the outer characters in a trigram (characters farthest from fixation), middle characters, and inner characters (those closest to fixation). They reported that sub-profiles for alphabet letters are broadest in the outer positions, followed by the inner positions, and narrowest for the middle positions. We conducted a similar analysis in this study for all the complexity groups in both full- and partial-report tasks (Appendix B). We found a similar pattern of results to Legge et al. (2001) for both alphabet and Chinese characters, which again supports the hypothesis that similar underlying sensory factors may apply to character recognition in different scripts.

Target-flanker similarity also appears to affect crowding. Bernard and Chung (2011) calculated the similarity scores for alphabet letters by using confusion matrices and found that identification errors for crowded letters increased with target-flanker similarity. Therefore, the increased crowding with complexity observed in our study might be confounded with pattern similarity. We used a normalized Euclidean distance method to compute the similarity for the stimulus sets (see Appendix A). The average similarity scores for each complexity group indicate that the similarity does increase with complexity for Chinese characters; however, the alphabet letters, despite having lowest complexity, have a similarity close to the median of the more complex Chinese characters (C3). It remains possible that perimetric complexity and similarity contribute separately to the decrease in visual spans for the more complex characters. The template-matching based similarity estimations used in the current study have been shown to be correlated with empirical data of pattern recognition in human observers. Geisler (1985) and Luce (1963) demonstrated that recognition accuracy (percent correct or d-prime) among multiple targets is monotonically related to the mean Euclidean distance of features between all pairs of targets. In addition, Watson and Ahumada (2012) tested a template model of visual acuity for alphabet and Chinese characters by comparing the model prediction to the acuity data from human observers. Their template model performed well, with high correlations between model and empirical data for the off-diagonal elements of the confusion matrices.

How does the spatial extent of crowding depend on pattern complexity? Bouma (1970) showed that critical spacing, defined as the minimum flanker-to-target spacing at which crowding is released, is determined by the eccentricity of the center target. Pelli et al. (2007) linked Bouma's law and the visual span and stated that the visual span is the uncrowded span, which is determined by inter-character spacing and not by properties of the target itself. However, it is known that empirical measures of critical spacing depend on threshold criteria and other factors (Levi, 2008; Whitney & Levi, 2011). Zhang et al. (2009) reported that the scaling factor relating critical spacing to the eccentricity varied between complexity groups of alphabet and Chinese characters, from 0.23 for Sloan letters to 0.37 for the most complex Chinese characters. Their finding is consistent with our finding that the visual span size varies with complexity at fixed center-to-center spacing.

Mislocation plays a secondary role in restricting the visual span. The degraded precision of character positioning in peripheral vision has been reported for alphabet letters (Chung & Legge, 2009; Strasburger, 2005; Strasburger, Harvey, & Rentschler, 1991) and Chinese characters of low complexity (Zhang, Zhang, Liu, & Yu, 2012). In our experiment, we showed that mislocation errors existed in all complexity groups. Mislocations were significantly more frequent for Chinese characters than for alphabet letters. This disparity might be attributed to overall differences among the two scripts. As Chinese characters all have a square shape, they may lose certain positioning landmarks present in alphabet letters (such as ascenders and descenders). In addition, Chinese characters typically share common components that may lead to confusion in the localization of ordered character strings.

The qualitative effect of complexity on the size of the visual span was preserved when the profiles were measured with a partial report procedure (one character reported on each trial) rather than full report (three characters reported). The difference in visual span sizes between full and partial reports, although relatively small, may reveal the influence of nonvisual cognitive factors. In the partial report procedure, the subject may focus spatial attention more narrowly in order to identify just one of three characters in the trigram. There is also a reduced memory demand in reporting just one of three characters. However, if these factors play a role, we believe they do not contribute independently, but interact with perceptual difficulty in our trigram task. We observed that recognition accuracy for trigrams centered on fixation with full report is close to 100% in all the complexity groups, implying that attention and memory don't necessarily limit recognition in the full report procedure (Figure 3). The difference in recognition accuracy between partial and full report is more apparent for trigrams further from fixation, which is associated with elevated crowding. Therefore, it is possible that as crowding increases with eccentricity, pattern recognition becomes more dependent on nonvisual cognitive influences.

巧克力吃多了会让人长胖
喝绿茶能降低癌症发病率

Figure 7. An example of two sentences with the same length and similar linguistic familiarity for Chinese readers but varied pattern complexity. The top sentence is less complex than the bottom. The translations of the top and bottom sentences are respectively "eating too much chocolate could make people fat" and "drinking green tea could reduce the possibility of cancer."

The visual span hypothesis argues that visual span is essentially a sensory bottleneck limiting reading speed (Legge et al., 2007). If this hypothesis generalizes to Chinese text, measurement of visual spans may provide insight into Chinese reading for both normally sighted and low-vision subjects. For example, we might predict that as the average complexity of characters in text goes up, reading speed will decrease. This idea might be testable by a within-subject comparison of reading speed for simplified and traditional Chinese characters; however, finding subjects equally familiar with the two systems would be a challenge. Alternatively, it may be possible to compare reading speeds for two sets of sentences composed of simplified Chinese characters, with sets matched in sentence length and linguistic complexity, but differing in pattern complexity. The following two sentences in Figure 7 provide an example. The perimetric complexity for the second sentence (bottom row) is 2.2 times larger than the first sentence (top row) although they share similar linguistic familiarity to Chinese readers.

Concluding remarks

In this study, we examined the effect of complexity on the visual span for alphabet and Chinese characters. A quantitative measure of spatial complexity suitable for both alphabetic letters and Chinese characters was developed based on the definition of perimetric complexity. We found that the size of the visual span significantly decreases with complexity. Crowding, which dramatically increases with complexity, is the major factor constraining the breadth of the visual span. Mislocation plays a secondary role in restricting the visual span. Our study extends the concept of visual span across different writing systems and implies that there might be common sensory constraints in character recognition. The strong association between visual span and reading speed for English text motivates future studies on developing objective Chinese reading tests for normal and low vision. Measures of pattern complexity may be useful for interpreting Chinese reading performance and characterizing the visual span for general object recognition.

Keywords: Chinese character recognition, visual span, complexity, crowding, peripheral vision, reading, Chinese reading

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Appendix A

Complexity measures

The objective was to divide the 700 most frequently used Chinese characters into five nonoverlapping categories based on their pattern complexity. Five definitions of complexity were investigated for this classification.

1. Stroke count

Strokes, referring to shapes that do not require a pen lift in writing, are the basic writing unit in Chinese characters. There are 31 fundamental strokes in the Chinese writing system, and each Chinese character has a fixed number of strokes. The complexity of a character is defined by the number of strokes. For the 700 most frequent Chinese characters, the number of strokes ranged between 1 and 16. A linear separation

	# of characters	# of strokes	Mean	*SD*
C1	48	1–3	2.69	0.51
C2	229	4–6	5.20	0.81
C3	267	7–9	7.97	0.81
C4	125	10–12	10.78	0.82
C5	31	13–16	13.81	0.91

Table A1. Statistics of the five complexity groups using stroke count measures.

	# of characters	Ink density	Mean	*SD*
C1	61	0.0302–0.0995	0.08	0.013
C2	151	0.1006–0.1199	0.11	0.006
C3	246	0.1200–0.1410	0.13	0.006
C4	197	0.1410–0.1579	0.15	0.005
C5	45	0.1580–0.1719	0.16	0.004

Table A2. Statistics of the five complexity groups using ink density measures.

was used to separate the characters into five complexity sets. The statistics are shown in Table A1.

2. Ink density

The width and height in the 700 Chinese characters (and most other characters) were the same; therefore, it is easy to treat a character as an image with fixed size. Each character was stored as a binary image, with the strokes in black (0) and background in white (1). The Heiti font was used to ensure equal thickness of all the strokes. The ink density is defined by the ratio of the number of zeroes and the total number of pixels in a character image. An approximately linear separation was applied to obtain five complexity groups. The detailed statistical description of grouping is shown in Table A2.

3. Stroke frequency

The stroke-frequency metric was used in Zhang et al. (2007). In brief, four groups of lines (horizontal, vertical, and diagonal) were drawn across the character. There were eight lines for the horizontal and vertical directions and four lines for each diagonal direction. The number of intersections between a line and the strokes was computed and defined as stroke frequency. The maximum number of intersections was used in each orientation of crossing lines, and the mean of them was referred to as the stroke frequency for the character. The 700 characters were approximately linearly divided into five complexity groups based on the stroke frequency values (Table A3).

	# of characters	Stroke frequency	Mean	*SD*
C1	71	0.83–2.67	2.27	0.41
C2	128	2.83–3.33	3.11	0.19
C3	128	3.5–4.17	3.86	0.23
C4	208	4.33–5	4.61	0.24
C5	40	5.17–6.5	5.46	0.29

Table A3. Statistics of the five complexity groups using stroke frequency measures.

	# of characters	Perimetric complexity	Mean	*SD*
C1	51	51–115	95.7	15.7
C2	156	116–155	139.7	10.9
C3	180	156–199	177.1	11.8
C4	168	200–245	217.3	12.6
C5	45	246–415	269.7	28.7
LL	26	30.1–75.4	48.6	11.7
UL	26	34.4–111.4	66.5	17.9

Table A4. Statistics of the five complexity groups using perimetric complexity measures.

4. Perimetric complexity

Perimetric complexity is defined as inside-and-outside perimeter squared divided by "ink" area (Arnoult & Attneave, 1956; Pelli et al., 2006). Pelli et al. (2006) estimated that perimetric complexity is roughly four times the aspect ratio of a stroke for stroked characters. Here we used an edge detection algorithm in Matlab to obtain the perimeter of a character, and the ink area was computed by the number of ink pixels. The 700 Chinese characters were classified into five groups by a roughly linear division based on the perimetric complexity scores. The perimetric complexities for lowercase and uppercase alphabet letters (LL and UL) are computed as well. The details of the statistics are described in Table A4.

5. Skeleton length

The length of the morphological skeleton has been used to represent the spatial complexity of alphabet letters (Bernard & Chung, 2011). We applied this measure to examine the complexity of Chinese characters (see Figure A1 for an example). The skeleton of a character was created by an image processing algorithm written in Matlab and the length of the skeleton was computed in pixels. As the stroke widths within a character are all the same in Heiti font, by definition

Figure A1. An example for Chinese character (black) and the constructed morphological skeleton (white). The complexity is defined as the length of the skeleton.

	Stroke count	Ink density	Stroke frequency	Perimetric
Stroke count	1	0.79	0.85	0.81
Ink density	0.79	1	0.93	0.83
Stroke frequency	0.85	0.93	1	0.89
Perimetric	0.81	0.83	0.89	1

Table A5. Rank-order correlation of the complexity scores derived from the four methods.

the skeleton length method is highly similar to the ink density method. We computed the complexities for the 700 Chinese characters and correlated the scores with ink density complexities. We found a correlation coefficient of 0.93. Therefore, in later comparisons we only consider the ink density method when correlated with the methods of stroke count, stroke frequency, and perimetric complexity.

Correlation between the complexity measures

A rank-order correlation on the complexity scores for the Chinese characters derived from the first four methods was conducted to examine whether the complexity assessment from the different measures were comparable. Table A5 shows that the correlations were near 0.8 or higher, indicating that the four complexity measures give similar information.

Because the measures of perimetric complexity have relatively high correlations with all other methods, and are suitable for alphabet letters as well, we decided to use perimetric complexity metrics to quantify the pattern complexity of Chinese characters and alphabet letters for the visual span test.

Similarity between characters

Most Chinese characters can be divided into subunits, which are commonly shared among multiple characters. These subunits usually have a restricted set of positions within the bounding box of the character and are spatially aligned between Characters. Therefore, the similarity between characters is more strongly influenced by the constituent features than by the spatial positions of the features. We used a normalized Euclidean distance measure to characterize the feature similarity between characters. Similarity between two characters is defined as follows:

$$d = \frac{2\sum_{i,j} C1_{i,j} C2_{i,j}}{\sum_{i,j} C1_{i,j} + \sum_{i,j} C1_{i,j}}, \tag{1}$$

where $C1_{i,j}$ and $C2_{i,j}$ are the values of pixel (i, j) on the binary images of character $C1$ and $C2$, respectively, assuming the strokes were coded one and the background was coded zero. The similarity scores range between zero and one. A value of zero means that there is no spatial overlap at all between the strokes of two characters, and a value of one means that the two characters are exactly the same.

Category	LL	UL	C1	C2	C3	C4	C5
Average similarity	0.38	0.40	0.30	0.38	0.42	0.48	0.48

Table A6. Similarity scores of the symbol categories.

Criteria for selection of stimulus sets

Twenty-six Chinese characters were selected from each complexity category to match the number of lowercase alphabet letters. The main criterion for selecting the stimulus set was to keep the differences of mean complexity between groups maximum and variations within group minimum, so the characters that have the complexity scores close to the mean of each group (within Mean ± *SD*) were selected first. In addition, similarity of characters was controlled in each group to eliminate characters that were too similar or dissimilar in the stimulus set. Characters with an average similarity score below 0.2 and above 0.65 were excluded.

Similarity scores of the stimulus sets

A similarity matrix (26 × 26) for each complexity group of the 26 symbols was obtained using the measure described above. To compare the within-category similarity between complexity sets, we computed the mean of the similarity matrices excluding the diagonals for each category. The average similarity scores are listed in Table A6.

Appendix B

Sub-profiles of the visual spans for inner, middle, and outer positions with full and partial report

The performance of character recognition within a trigram depends on the relative position of the character. We separated the visual span profile into sub-profiles representing recognition for characters in the three positions—inner (nearest to the midline), middle (center of the trigram), and outer (farthest from

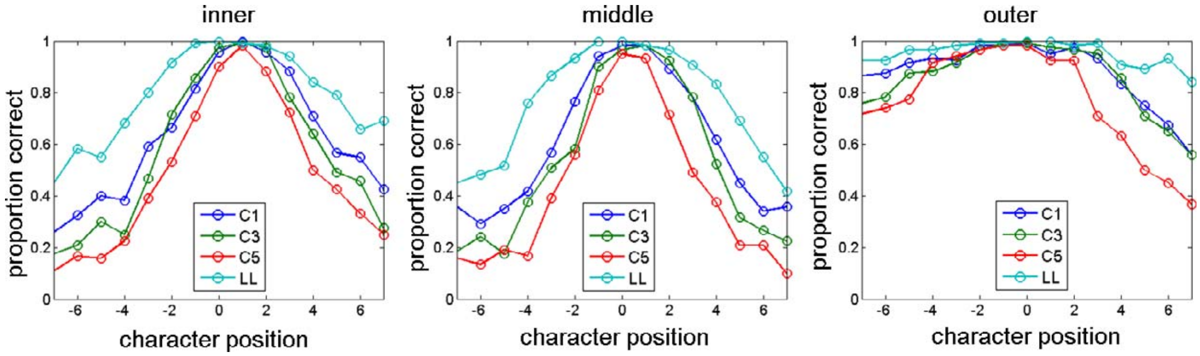

Figure B1. Sub-profiles of the visual span are shown for characters in the inner, middle, and outer positions within trigrams when the full report procedure was used. The four complexity groups (LL, C1, C3, and C5) are shown on each plot.

the midline). We asked whether the complexity effect was evident in the sub-profiles.

1. Sub-profiles for inner, middle, and outer positions with full report

The sub-profiles of the four complexity groups with full report are shown in Figure B1 for characters in the inner, middle, and outer positions. The effect of pattern complexity is evident in all three cases: the profiles get narrower with increasing complexity. The sub-profiles for inner and outer characters are asymmetric, being broader to the right of the midline for the inner characters and to the left of the midline for the outer characters. This asymmetry may be due to the left-to-right response order in the full report. For example, for trigrams presented in the left visual field, the "outer" character is reported first, but for trigrams in the right visual field, the "outer" character is reported last.

These sub-profiles are replotted in Figure B2 to enable direct comparison of the plots for the inner, middle, and outer characters. Consistent with the earlier report for alphabet letters (Legge et al., 2001), the outer characters have the broadest profiles, followed by the inner and middle characters. This pattern is similar in all the complexity groups.

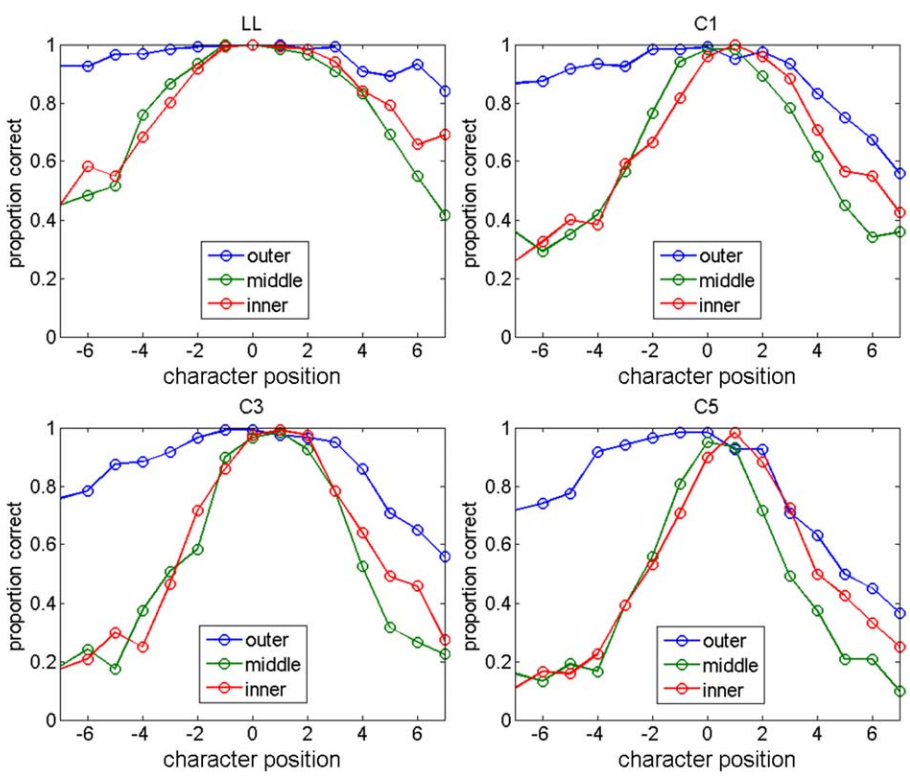

Figure B2. The sub-profiles in Figure B1 are replotted to show the relationships between character recognition in the inner, middle, and outer characters for the four complexity groups.

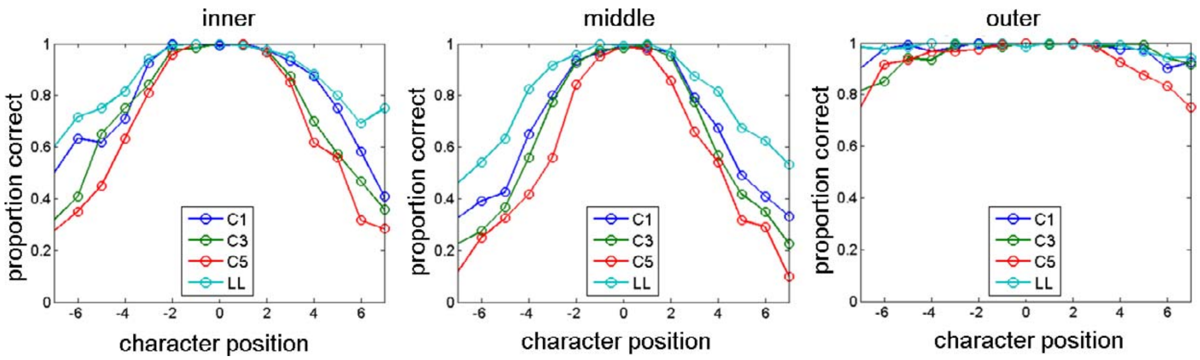

Figure B3. Sub-profiles of the visual span are shown for characters in the inner, middle, and outer positions within trigrams when the partial report procedure was used. The four complexity groups (LL, C1, C3, C5) are shown on each plot.

2. Sub-profiles for inner, middle, and outer positions with partial report

The sub-profiles of the four complexity groups with partial report are shown in Figure B3 for characters in the inner, middle, and outer positions. The effect of pattern complexity is similar to the full reports: the sub-profiles get narrower with increasing complexity. The asymmetry of the inner and outer sub-profiles as observed in full report disappears, because only one character recognition was required each time in partial report. These sub-profiles are replotted in Figure B4 to enable direct comparison of the plots for the inner, middle, and outer characters. The sub-profile for the outer characters is much broader than the inner and middle sub-profiles and approaches that for isolated characters (Figure B4). Similar to the full report, the lowest recognition accuracy is found for the middle characters, while the difference between middle and inner positions is small.

3. Comparison between full and partial reports

We computed the sizes of the sub-profiles for full and partial reports. Size of the sub-profiles was defined as the breadth of the curves for an accuracy

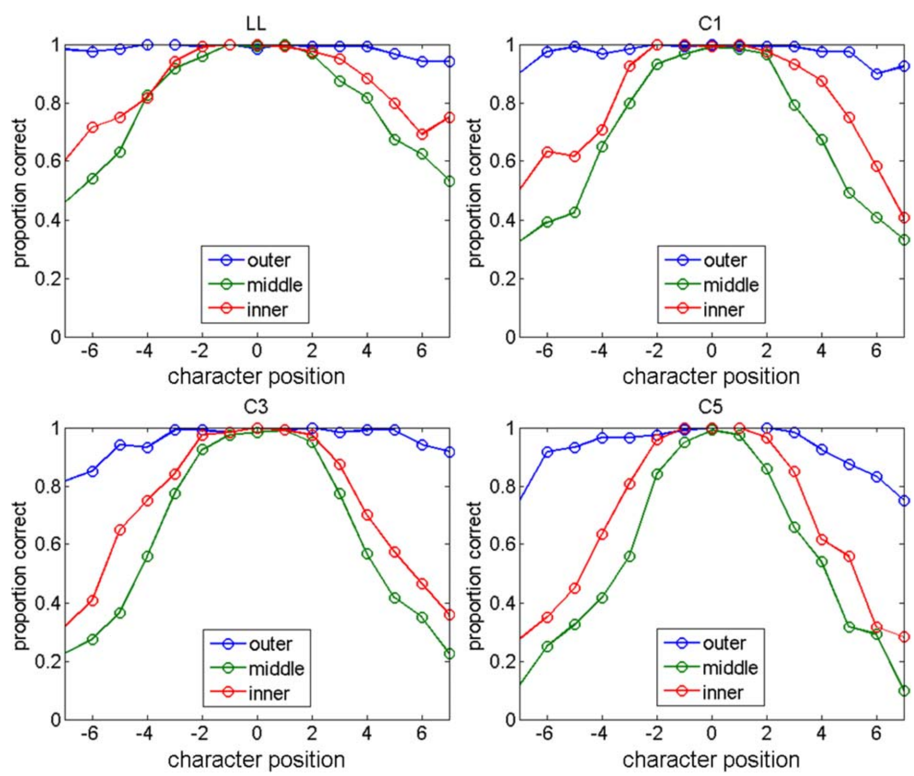

Figure B4. The sub-profiles in Figure B3 are replotted to show the relationships between inner, middle, and outer characters for the four complexity groups.

criterion of 80% correct. Because the sub-profiles for outer characters sometimes did not drop below 80%, we restricted this analysis to sub-profiles for inner and middle characters. The results are summarized in Table B1. Comparing the sub-profile sizes between the full and partial reports, a difference of approximately three characters was found for the inner positions, while the difference was reduced to about one character for the middle positions.

	Full report		Partial report	
	Inner	Middle	Inner	Middle
LL	9.5 ± 0.63	8.6 ± 0.57	12.3 ± 1.09	9.2 ± 0.59
C1	6.2 ± 0.43	5.8 ± 0.39	9.4 ± 0.61	7.1 ± 0.47
C3	5.7 ± 0.24	5.2 ± 0.26	8.0 ± 0.57	6.5 ± 0.43
C5	4.5 ± 0.58	3.8 ± 0.65	7.2 ± 0.52	5.6 ± 0.56

Table B1. The sub-profile sizes (Mean ± *SE*) for inner and middle characters with full and partial reports.