REPORT

Vernier But Not Grating Acuity Contributes to an Early Stage of Visual Word Processing

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Abstract The process of reading words depends heavily on efficient visual skills, including analyzing and decomposing basic visual features. Surprisingly, previous reading-related studies have almost exclusively focused on gross aspects of visual skills, while only very few have investigated the role of finer skills. The present study filled this gap and examined the relations of two finer visual skills measured by grating acuity (the ability to resolve periodic luminance variations across space) and Vernier acuity (the ability to detect/discriminate relative locations of features) to Chinese character-processing as measured by character form-matching and lexical decision tasks in skilled adult readers. The results showed that Vernier acuity was significantly correlated with performance in character form-matching but not visual symbol form-matching, while no correlation was found between grating acuity and character processing. Interestingly, we found no correlation of the two visual skills with lexical decision

performance. These findings provide for the first time empirical evidence that the finer visual skills, particularly as reflected in Vernier acuity, may directly contribute to an early stage of hierarchical word processing.

Keywords Visual word processing · Vernier acuity · Grating acuity · Visual skill

Introduction

Theoretical models of visual word-processing suggest that it starts with the analysis of basic visual features [1–8]. When a word is presented, the visual lexical information is first processed by the orthographic subsystem on the basis of basic visual features (e.g., local contrasts, oriented bars, and local contours/orthographic fragments) [1, 2]. It is therefore likely that the skills of analyzing and decomposing these basic visual features are crucial for visual word-processing, and ultimately word recognition [1, 2, 9]. However, studies have mainly focused on the gross aspects of visual skills including visuo-spatial skills (e.g., visuo-spatial attention [10–14], visual-paired associate learning [15, 16], and visual memory [17]), while only very few have investigated the link between finer visual skills and word-processing, although it has been proposed that such skills may be necessary for efficient processing [1, 2, 9].

There are two fundamental finer visual skills, typically measured by grating acuity and Vernier acuity. While grating acuity measures the ability to resolve periodic luminance variations across space, Vernier acuity measures the ability to detect/discriminate the relative locations of features [9]. It is likely that grating acuity is the basis for detecting and resolving simple features of words [1]. In other words, if the visual stimuli (in this case words) are

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too small (or presented too far away), reading would be difficult since the visual system would not be able to resolve the individual strokes. In contrast, Vernier acuity relies on the ability to detect spatial relationships at very fine scales [1], and this is critical for differentiating similar letters and words (or similar Chinese characters). Therefore, these skills may be important for different aspects of efficient word or character processing. However, no studies have tested this hypothesis.

This study was designed to investigate the relationship between Chinese character processing and the two types of finer visual skills in skilled adult readers.

Participants and Methods

Experiment 1

Participants

Twenty-seven Chinese readers (10 male and 17 female college students aged 20.52 ± 2.01 years, with 14.33 ± 1.59 years of formal education) participated in the experiment. All were right-handed with normal or corrected-to-normal vision. This study was approved by the Ethics Review Board of the authors' institution, and all participants gave written informed consent.

Stimuli and Procedures

Visual Acuity Tests Participants were seated in a dimly-lit room. All tests were preceded by 15 min of dark-adaptation to ensure that the participants' eyes were adapted to the luminance of the background color of the screen, to ensure maximal sensitivity. The stimuli were generated and displayed using MATLAB (MathWorks, Inc., MA) together with Psychophysics Toolbox Version 3 (PTB-3 [18, 19]). They were presented on a 19-inch CRT monitor (Samsung SyncMaster 959NF, 1920×1440 pixels, at 60 Hz) at a viewing distance of 900 cm. With this set-up, one pixel subtended 0.06 arcmin (1 arcmin = 1/60 of a degree) of visual angle.

Grating Acuity Test. The stimulus for this test was a grey-and-white square-wave grating. The Michelson contrast of the gratings was set to be 98% with a mean luminance of 99 cd/m² [20]. This was also the luminance of the grey background. In each trial, a grating was displayed either horizontally or vertically (Fig. 1A). Participants were instructed to judge the orientation of the grating, and press the leftward arrow key (←) for a horizontal stimulus or the upward arrow key (↑) for a vertical stimulus. The stimulus was present until a key response was made (Fig. 1A).

A 3-up-1-down staircase procedure was used to measure grating acuity for each participant. The initial spatial frequency of a grating was 4 cyc/deg (i.e., units of spatial frequency, equal to the number of cycles in grating [one dark and one light band] that subtend 1 degree of visual angle). Specifically, the spatial frequency was increased by 1 octave after 3 consecutive correct responses, and decreased by 0.5 octave after 1 incorrect response. Thirty-five staircase reversals (one reversal refers to a change from going up to going down or reversed in the staircase procedure) were obtained for each participant. The grating acuity was defined as the average of the last 15 reversal points to ensure that the threshold had reached stability. This staircase provided an estimated threshold of 79.4% correct [21, 22]. The threshold represented the highest spatial frequency that a participant was able to recognize. Thus, a higher threshold reflected better grating acuity.

Vernier Acuity Test. The stimulus for this test was a bright vertical bar (Vernier bar) on a gray background in the midline of the screen, which was split into two segments in the middle. The two segments were displaced horizontally to a certain degree, and each was 45 arcmin in length and 12 arcmin in width. The lower segment was shifted leftward or rightward relative to the upper segment (Fig. 1B). Participants were instructed to judge the offset direction of the lower segment relative to the upper segment by pressing the leftward or rightward arrow key. The initial offset of the Vernier bar was set to be 1 arcmin. The procedure and acuity calculation were the same as those in the grating acuity test. The threshold represented the minimum offset that a participant was able to recognize. Thus, a lower threshold reflected a better Vernier acuity.

Visual Form-Matching Tests Two visual form tests were performed: visual character form-matching and visual symbol form-matching. In both tests, stimuli were displayed using E-prime 2.0 software [23], and were presented on a 17-inch CRT monitor (1024×768 pixels at 60 Hz) at a viewing distance of 100 cm.

Character Form-Matching Test. Sixty left-right structured Chinese characters were used. The number of strokes ranged from 5 to 9. The characters were presented in 72-point, STKaiti font. Each pair of characters only differed in one or two strokes (Fig. 2A). The trial started with a fixed cross presented at the center of the screen for 800 ms. The stimulus pair was displayed for 200 ms (Fig. 2B). All stimuli were presented in black against a grey background, and subtended $\sim 1.3^\circ$ of visual angle at a viewing distance of 100 cm. Horizontally, the two characters were $\sim 3.6^\circ$ of visual angle apart.

Fig. 1 Examples of stimuli and sketches of the experimental procedures in the grating (A) and Vernier (B) acuity tests.

Fig. 2 Examples of stimuli (A) and the sketches of the experimental procedures in the character form-matching test (B) in Experiment 1 and the stroke combination-matching test (C) in Experiment 2.

Participants were instructed to decide whether the two Chinese characters were the same or different and press one of two buttons as quickly as possible while minimizing errors (i.e., character form-matching task [24]) (Fig. 2B). Before the test, the participants performed 40 training trials (60 or 80 trials for some participants) until they reached an accuracy of 80%. The test was composed of 60 trials, 30 “Same” trials and 30 “Different” trials. The Chinese characters used in the test were different from those in the training session. The order of trials was randomized and the keys corresponding to Same/Different responses were counterbalanced across participants.

Visual Symbol Form-Matching Test. To determine whether visual acuity was specifically related to word processing, a symbol form-matching test (e.g., ㄣ ㄣ) was used as a control task. The procedure was the same as that in the character form-matching test.

Data Analysis

As discussed in the introduction, based on the existing theories and empirical studies in the literature, we generated clear hypotheses on the relationship between character form-matching and the two types of finer visual skills. Therefore, planned correlation analyses were performed to

test the hypotheses. Specifically, the correlation between accuracy in the character form-matching task and Vernier acuity or grating acuity was computed for each case. To further determine whether visual acuity was related to character but not general visual form-processing, the correlation between accuracy in the symbol form-matching task and each of the two kinds of visual acuity was computed.

Results

The means and standard deviations for the visual acuity and visual form-matching tasks are listed in Table 1. The average grating acuity was 37.65 cyc/deg, and the average Vernier acuity was 0.25 arcmin. The average accuracy in the character and visual symbol form-matching tasks was 0.72 and 0.95, respectively. We next computed the correlation between accuracy in the character (or symbol) form-matching task and each of the two types of visual acuity. The results showed that Vernier acuity was correlated with accuracy in the character form-matching task ($r = -0.40$, $P = 0.04$; Fig. 3A). In contrast, no significant correlation was found between Vernier acuity and accuracy in the visual symbol form-matching task ($r = -0.15$, $P = 0.44$; Fig. 3B). In addition, we found no significant correlation between grating acuity and accuracy either in the character form-matching task ($r = 0.18$, $P = 0.37$), or in the visual symbol form-matching task ($r = 0.01$, $P = 0.98$) (Fig. 3C, D).

Discussion

The results in Experiment 1 showed that the Vernier acuity was associated with accuracy in character form-matching but not in symbol form-processing. Moreover, finer visual

skills, particularly as measured by Vernier acuity, may be more important for visual word-processing, suggested by the absence of a significant correlation between grating acuity and accuracy in character form-matching. Nevertheless, it is also notable that the accuracy in symbol form-matching was close to a ceiling. This may also have contributed to the null correlation between Vernier acuity and accuracy in the symbol form-matching task. Furthermore, symbol forms may not match well with characters in visual complexity. To control these potential confounding factors, we used stroke combinations as control stimuli in Experiment 2, to verify the null result of the correlation between grating acuity and character processing.

Experiment 2

Participants

A new group of 29 Chinese readers (5 male and 24 female college students aged 20.10 ± 1.52 years, with 14.41 ± 1.27 years of formal education) participated in the experiment. All were right-handed with normal or corrected-to-normal vision.

Stimuli and Procedures

The stimuli in visual acuity were the same as in Experiment 1. The Chinese characters used in character form-matching task were newly-selected. Similar to the stimuli used in Experiment 1, stimuli of character pairs differed in terms of the number and orientation of one or two strokes (Fig. 2A). Stroke combinations were constructed by recombining the strokes of the Chinese characters in the character form-matching task (Fig. 2A) and matched with

Table 1 Descriptive statistics of all behavioral measures.

	Measure	Mean	SD
Experiment 1	Grating acuity (cyc/deg)	37.65	8.92
	Vernier acuity (arcmin)	0.25	0.09
	Character matching accuracy	0.72	0.07
	Visual symbol matching accuracy	0.95	0.04
Experiment 2	Grating acuity (cyc/deg)	31.51	8.63
	Vernier acuity (arcmin)	0.32	0.11
	Character matching accuracy	0.74	0.07
	Visual stroke combination matching accuracy	0.72	0.08
Experiment 3	Grating acuity (cyc/deg)	38.11	5.57
	Vernier acuity (arcmin)	0.25	0.09
	Character matching accuracy	0.73	0.06
	Visual complicated symbol matching accuracy	0.82	0.06
	Lexical decision hit rate	0.95	0.05
	Lexical decision false-alarm rate	0.28	0.08

Fig. 3 Scatterplots between Vernier acuity and accuracy in character form-matching (A) and symbol-matching (B), and between grating acuity and accuracy in character form-matching (C) and symbol-matching (D).

them in visual complexity (e.g., strokes and number of strokes; see Zhao *et al.*, 2012 for further discussion [25]).

The task and procedure were similar to those in Experiment 1 except that the duration of stroke combination in the visual form-matching task was prolonged to 600 ms (Fig. 2C) based on the results of a pilot study, to make the difficulty of the stroke combination-matching task comparable with that of the character form-matching task.

Results

Means and standard deviations for the visual acuity and visual form-matching tasks are shown in Table 1. The average grating acuity was 31.51 cyc/deg, and the average Vernier acuity was 0.32 arcmin. The average accuracy in the character-matching task was 0.74, and that in the visual stroke combination-matching task was 0.72. The Vernier acuity was correlated with accuracy in the character form-matching task ($r = -0.38$, $P = 0.04$; Fig. 4A), but not correlated with accuracy in the stroke combination-matching task ($r = -0.32$, $P = 0.09$; Fig. 4B). No significant correlation was found between grating acuity and accuracy either in the character form-matching task ($r = 0.05$,

$P = 0.80$) or in the stroke combination-matching task ($r = 0.001$, $P = 0.99$) (Fig. 4C, D).

Discussion

Consistent with the results in Experiment 1, we found that the Vernier acuity correlated with accuracy in character form-matching. No correlation was found between grating acuity and accuracy in character form-matching, which further confirmed the findings in Experiment 1. However, it is important that there was a trend of correlation between Vernier acuity and accuracy in stroke combination form-matching. This may be because the stroke combinations, constructed by recombining the strokes of Chinese characters, are still visually similar to these characters, and the stroke combination form-matching task also involves processes of feature localization such as orientation and displacement. To further test this interpretation, we used complicated symbols as control stimuli in Experiment 3. The complicated symbols, constructed by combining several simple symbols, had few characteristics of the visual forms of Chinese characters, and the matching task thus involved little processing of fine-grained feature discrimination. In addition, the task of complicated

Fig. 4 Scatterplots between Vernier acuity and accuracy in character form-matching (A) and stroke combination-matching (B), and between grating acuity and accuracy in character form-matching (C) and stroke combination-matching (D).

symbol-matching was more difficult than the symbol form-matching task, excluding the ceiling effect in Experiment 1.

The visual form-matching task is a common tool to test the process of detecting the fine-grained features of word form, at an early stage of hierarchical word processing (see local combination detector model in Dehaene *et al.*, 2005; Cohen and Dehaene, 2009 [1, 2]). To further clarify the exact role of Vernier acuity in visual word processing, we increased the number of participants and used a lexical decision task in Experiment 3. Lexical decision mainly relies on higher-level linguistic processes, and involves little basic visual feature-processing.

Experiment 3

Participants

A new group of 46 Chinese readers (9 male and 37 female college students aged 21.59 ± 1.87 years, with 15.13 ± 1.24 years of formal education) participated in

the experiment. All were right-handed with normal or corrected-to-normal vision.

Stimuli and Procedures

Visual Acuity Tests The same as in Experiments 1 and 2.

Visual Form-Matching Task The stimuli, except for visual control stimuli (complicated symbols), were the same as in Experiment 2. The complicated symbols were combined from several simple symbols, and the two complicated symbols in each pair were similar to each other (e.g.). The task and procedure were the same as in Experiment 1.

Lexical Decision Task Four types of stimuli were used: real characters, pseudo-characters, false characters, and stroke combinations. The Chinese characters consisted of 60 left-right structured characters. The pseudo-characters were constructed by combining the radicals of the real characters, in which both radicals were at commonly-appearing positions. The false-characters were made by

exchanging the positions of radicals of the pseudo-characters, in which both radicals were at uncommon positions. Stroke combinations were constructed by recombining the strokes of the false characters. There were 30 items in each type of non-character stimuli. Examples are illustrated in Fig. 5A. Each trial started with a fixation cross presented at the center of the screen for 600 ms to 800 ms randomly. A stimulus was displayed for 300 ms (Fig. 5B). All stimuli were presented in black against a grey background, and subtended $\sim 1.3^\circ$ of visual angle at a viewing distance of 100 cm.

Participants were instructed to decide whether or not each stimulus was a real Chinese character, and press one of the two mouse buttons as quickly as possible while minimizing errors (Fig. 5B). The order of trials was randomized and the keys corresponding to yes/no were counterbalanced across participants.

Results

The means and standard deviations for visual acuity, visual form matching, and lexical decision tasks are listed in Table 1. The average grating acuity was 38.11 cyc/deg, and the average Vernier acuity was 0.25 arcmin. The average accuracy in the character-matching task was 0.73, while the accuracy in the complicated symbol-matching task was 0.82. The average hit rate in the lexical decision task was 0.95, and the false-alarm rate was 0.28.

The Vernier acuity was correlated with accuracy in the character form-matching task ($r = -0.38$, $P = 0.009$; Fig. 6A), but not accuracy in the complicated symbol-matching task ($r = -0.22$, $P = 0.15$; Fig. 6B). No significant correlation was found between grating acuity and accuracy either in the character form-matching task ($r = 0.11$, $P = 0.49$; Fig. 6C) or in the complicated symbol-matching task ($r = 0.05$, $P = 0.75$; Fig. 6D). In addition, there was no significant correlation between Vernier

acuity and lexical decision performance (hit rate, $r = 0.14$, $P = 0.35$; false-alarm rate, $r = 0.20$, $P = 0.18$).

Discussion

Consistent with the results in Experiments 1 and 2, we found that the Vernier acuity was significantly correlated with accuracy in character form-matching, but not in complicated symbol form-processing. Moreover, with a larger sample of participants, the correlation between Vernier acuity and character form-matching was significant even after multiple comparison correction. No correlation was found between grating acuity and accuracy in the character form-matching task. These results further confirmed the findings in Experiments 1 and 2. Compared with stroke combinations, complicated symbols were apparently less similar to real characters in terms of basic visual features, and the complicated symbol-matching task likely involved little fine-grained feature discrimination. Therefore, we found no correlation between Vernier acuity and complicated symbol form-matching. These results combined with those in Experiments 1 and 2 suggest that Vernier acuity does play a relatively specific role in visual word-processing (at an early stage) rather than general visual-form processing. However, lexical decisions almost exclusively rely on higher-level linguistic processes, which may involve little or no basic visual feature processing. This may be the reason why we did not find a significant correlation between performance in the lexical decision task and Vernier acuity in Experiment 3.

General Discussion

In this study, we investigated whether the two types of fundamental finer visual skills are related to Chinese character-processing in skilled adult readers. The results showed that the Vernier acuity rather than the grating

Fig. 5 Examples of stimuli (A) and sketches of the experimental procedure in the lexical decision test (B) in Experiment 3.

Fig. 6 Scatterplots between Vernier acuity and accuracy in character form-matching (**A**) and complicated symbol-matching (**B**), and between grating acuity and accuracy in character form-matching (**C**) and complicated symbol-matching (**D**).

acuity was significantly correlated with character form-matching. Moreover, the correlation between Vernier acuity and the performance of lexical decision was not significant, suggesting that the Vernier acuity mainly contributes to an early stage of hierarchical word-processing rather than higher-level linguistic processes. This study extends previous work on gross and finer visual skills and provides empirical evidence for a role of finer visual skills in visual word-processing.

The Vernier acuity reflects processes of feature localization, such as orientation and displacement. And the process of detecting fine-grained features of visual word form (e.g., orientation and displacement) is thought to be a very early stage of hierarchical word-processing [1, 2]. Therefore, one possible reason for the finding that Vernier acuity was correlated with word form-processing is that both are related to the process of orientation discrimination [9, 26, 27]. Unlike grating acuity, Vernier acuity is a type of hyperacuity. Observers can often detect Vernier offsets smaller than the diameter and spacing of retinal receptors. Therefore, Vernier acuity involves more integration and cortical processing [28]. Indeed, it has been suggested that

the orientation-specific receptive fields in V1 cortex are important for the detection of Vernier offset [29].

Interestingly, we did not find a significant correlation between grating acuity and Chinese character-processing. Grating acuity measures the resolution of periodic luminance variations across space and reflects simple feature-detection/resolution, while Vernier acuity measures the relative positions of features and reflects the detection/discrimination of spatial relationships at very fine scales. The paired stimuli used in our visual character form-matching task differed in the number and orientation of one or two strokes (Fig. 2A, B), thus performance in this task depended on detection/discrimination of the relationships among the strokes. Therefore, the ability to detect spatial relationships at very fine scales (i.e., Vernier acuity) is more important for the character form-matching task. The current finding further supports the idea that the type of finer skill measured by Vernier acuity that requires more extensive integration of visual inputs is important for the visual processing of words.

There is another possibility for the finding that Vernier acuity was correlated with accuracy in the character form-matching task. Previous studies have shown that while the

grating acuity reaches full maturity, the Vernier acuity begins its final phase of development at the age at which children usually start to learn to read words (6 years) [9]. Although the visual system in nonhuman primates is similar to that of humans, monkeys lack the second phase of development of Vernier acuity, possibly because they have no reading experience [30]. Since words are cultural inventions, it is possible that human beings have developed and modified existing visual skills (such as Vernier acuity) for word reading, rather than developing a new skill specific for reading.

Our findings are consistent with results in the literature. For example, the response of primary visual cortex to words is enhanced with increased literacy [31] and stronger compared to that to objects in the primary visual areas [32]. However, it should be noted that two earlier studies did not find a significant difference in Vernier acuity between dyslexic and normal adults who read alphabetic text [33, 34]. Several factors may have led to the discrepancy between these findings and ours. Most importantly, the performance of Vernier acuity in both studies [33, 34] was quite a bit poorer than the typical Vernier acuity reported in the literature (e.g., [9, 18]) and our study. This suggests that the measurement of Vernier acuity in both studies may not have been sufficiently sensitive to reveal differences between the dyslexic and normal groups.

There are some limitations in this study. First, it was conducted in adult readers. As discussed above, the developmental trajectories of grating acuity and Vernier acuity differ. While grating acuity reaches full maturity at ~ 6 years, the Vernier acuity begins its final phase of development at this age [9]. It is thus important to further examine the relationships between different types of fine visual skills and word-processing at different developmental stages with different reading experiences. Second, this study was conducted in Chinese readers, and the stimuli were Chinese characters. Previous studies have shown that some gross visual perceptual skills such as visual spatial skill and visual paired associate learning skill are more important for the processing of Chinese than other scripts due to the complex visual orthography of Chinese characters (see Zhou & McBride-Chang, 2014 for a review [35]). Thus, to further address whether our current findings can be generalized to other writing systems, it is of theoretical interest to extend the present study to other scripts with different visual features such as English. Third, in future studies, brain imaging techniques can be used to examine the exact role of Vernier acuity in reading [36, 37]. Finally, we did not determine the number of participants before we conducted the study and the numbers differed among the three experiments, although this limitation seems unlikely to have significantly influenced our main results.

To summarize, the present study revealed that Vernier acuity was correlated with the processing of Chinese characters but not with the processing of other visual stimuli. In contrast, the grating acuity was not significantly correlated with character form-matching accuracy. In addition, no correlation was found between the two visual skills and lexical decision performance. These findings highlight the potentially shared mechanism between Vernier acuity and early stages of visual word-processing, presumably because they both depend on the processing of finer visual features and require extensive integration of visual inputs.

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Compliance with Ethical Standards

Conflict of interest All authors claim that there are no conflicts of interest.

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