Holistic processing as a hallmark of perceptual expertise for nonface categories including Chinese characters

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Holistic processing has been associated with perceptual expertise in different domains involving faces, cars, fingerprints, musical notes, English words, etc. Curiously Chinese characters are regarded as an exception, as indicated by reduced holistic processing found for experts with the Chinese writing system as compared with novices. We revisit the issue and examine one type of holistic processing, the obligatory attention to all parts of an object, using the composite paradigm from face perception literature. Chinese readers (experts) and non-Chinese readers (novices) matched the target halves of two characters while ignoring the irrelevant halves. We introduced differential response deadlines for experts and novices in order to match their performance level and to avoid ceiling performance for experts. Both experts and novices showed holistic processing, irrespective of the character structure (left-right or top-bottom) or presentation sequence (sequential or simultaneous matching). Experts' holistic processing also showed some sensitivity to the amount of experience with the characters, as it was larger for characters than noncharacters in some situations. Novices, however, did not show a systematic difference, suggesting that their effects were more related to their inefficient decomposition of a novel, complex pattern into parts. The current results, together with other recent findings of holistic processing for English words and musical notes, indicate that the development of holistic processing is not restricted to faces and objects. Instead it may be a general marker of expertise across a wider domain of visual discrimination than previously thought, including alphabetic and nonalphabetic writing systems.

Keywords: perceptual expertise, holistic processing, letter perception, word recognition, Chinese characters

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Introduction

For faces, cars, chessboards, fingerprints, etc., perceptual expertise with different object categories is associated with holistic processing (Bilalić, Langner, Ulrich, & Grodd, 2011; Bukach, Phillips, & Gauthier, 2010; Busey & Vanderkolk, 2005; Chase & Simon, 1973; Gauthier, Curran, Curby, & Collins, 2003; Richler, Tanaka, Brown, & Gauthier, 2008). Holistic

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processing is typically defined as either the obligatory attention to all parts of an object (Hole, 1994; Richler, Tanaka et al., 2008) or the sensitivity to the detailed spatial relationships between parts (Maurer, LeGrand, & Mondloch, 2002). One common understanding is that perceptual expertise typically involves fine, subordinate-level discrimination between highly similar objects (e.g., differentiating between faces of two siblings or between two fingerprints), and during the acquisition of expertise, holistic processing develops as an optimal way to fulfill the demand of fine discrimination (Bukach, Bub, Gauthier, & Tarr, 2006). This claim has been supported by the association between identification performance and holistic processing of faces (Richler, Cheung, & Gauthier, 2011; but see Konar, Bennett, & Sekuler, 2009). Furthermore, training studies with novel objects have demonstrated that holistic processing develops after training that requires subordinate-level individuation, but not following training that involves coarser, basic-level categorization of objects (Nishimura & Maurer, 2008; A. C.-N. Wong, Palmeri, & Gauthier, 2009).

Expertise with text seems to represent a different type of perceptual expertise from the face-like, subordinate-level expertise described above. In terms of task demand, recognition of words and letters/characters requires coarser, basic-level categorization (A. C.-N. Wong & Gauthier, 2007; Zhang & Cottrell, 2004). For all writing systems, words differ from each other in terms of the number and identity of their constituent parts (e.g., how many and what letters there are and their order in a word). The detailed spatial relationships between parts (e.g., the distance between letters) seem less important for identifying a word. Text also exhibits a different pattern of neural selectivity compared with faces and other objects of expertise. Characters in alphabetic and nonalphabetic writing systems recruit more lateral and left-dominant regions of the occipitotemporal cortex, compared with face-selective areas that are generally more medial and prevalent in the right hemisphere (Levy, Hasson, Avidan, Hendler, & Malach, 2001; A. C.-N.Wong, Jobard, James, James, & Gauthier, 2009). Farah (1991) and Farah, Wilson, Drain, and Tanaka (1998) place word and face perception at the two extremes of a processing continuum: At one extreme is the part-based processing of words, and at the other is the holistic processing of faces, while other objects lie somewhere in between.

Different paradigms have been used to examine if words are processed holistically, and results are mixed. The famous word superiority effect highlights the role of whole-word representations in the identification of letters (Reicher, 1969; Wheeler, 1970). Word identification can sometimes even bypass recognition of its constituent letters (Jordan, Thomas, & Scott-Brown, 1999; Perea, Duñabeitia, & Carreiras, 2008). Word shape processing has also been shown to play an important role in efficient reading (Grainger & Whitney, 2004; Osswald, Humphreys, & Olson, 2002; Pelli & Tillman, 2007). In contrast, other studies have emphasized the importance of part isolation and identification in word recognition (Farah et al., 1998; Martelli, Majaj, & Pelli, 2005; Pelli, Farell, & Moore, 2003). Since the majority of studies examining holistic processing of text have used paradigms different from those used for faces and other objects of subordinate-level expertise, it is difficult to make a direct comparison across domains.

Recently we adopted a composite matching paradigm widely used for faces and showed expertise-related holistic processing of English words (A. C.-N. Wong, Bukach et al., 2011). Two four-letter words were shown sequentially, and observers had to judge if the target parts (either the left or right halves) of the two words were identical or not while ignoring the other, irrelevant part (Figure 1). Responses were faster for the congruent condition (both left and right halves the same or both different) than the incongruent condition (one half the same and the other half different), indicating the obligatory attention to all parts despite the instruction to focus only on the target part. This congruency effect was also dependent on the configu-

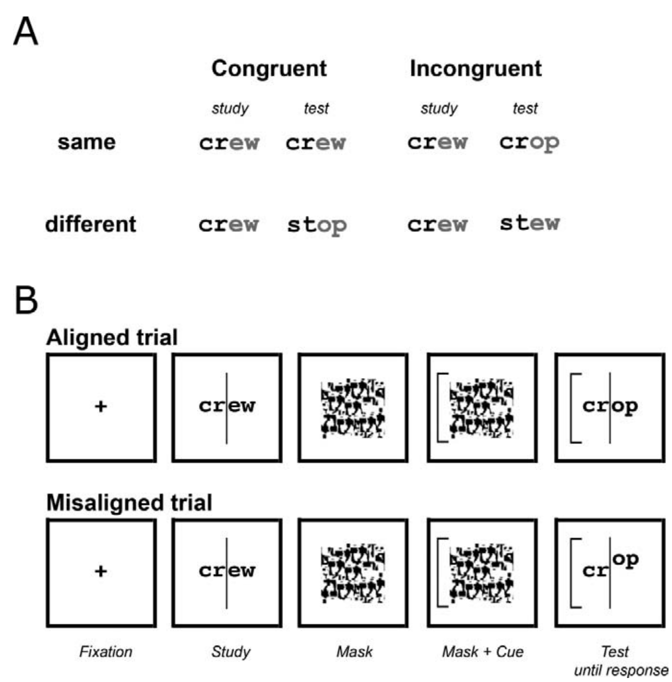

Figure 1. (A) An example set of English word stimuli used in A. C.-N. Wong, Bukach et al. (2011). This assignment to conditions is for trials in which matching of the left part is required. The black parts had to be attended to while the gray parts had to be ignored (for illustration only; in the actual experiment, both parts were black). (B) Trial sequence, where the two composites were presented sequentially.

ration of the parts, as it was larger when the two parts were aligned versus misaligned. Such a performance pattern was characteristic of holistic face processing. We further found that holistic processing of words was larger for native English readers than readers learning English as their second language, who can be regarded as intermediate experts with English words. Also the effects were larger for words than nonwords for the native readers. These results suggest that holistic processing develops as one acquires more experience with a writing system and with the specific words.

The current study examined whether holistic processing can also be found as one develops expertise with characters in nonalphabetic writing systems, focusing on the example of Chinese. Specifically, we asked if selective attention to different parts of a Chinese character is obligatory during word processing. There are reasons to expect this to be the case. First, common behavioral markers and neural selectivity patterns have been found for expert processing of characters in alphabetic and nonalphabetic writing systems (Gauthier, Wong, Hayward, & Cheung, 2006; A. C.-N. Wong & Gauthier, 2007; A. C.-N. Wong, Gauthier, Woroch, Debuse, & Curran, 2005; A. C.-N. Wong, Jobard et al., 2009; A. C.-N. Wong, Qu, McGugin, & Gauthier, 2011). In addition, previous studies have shown the importance of structural information, or the spatial arrangement of the components, in the perception of a character (Yeh & Li, 2002; Yeh, Li, Takeuchi, Sun, & Liu, 2003; but see Ge, Wang, McCleery, & Lee, 2006).

Curiously, however, a study using a similar composite paradigm as the one we used for English words showed a very different pattern of results for Chinese characters (Hsiao & Cottrell, 2009). Two-part characters with a top-bottom configuration were used and observers judged if the target parts (top or bottom) of two simultaneously presented characters were the same while ignoring the irrelevant parts. Surprisingly, non-Chinese readers showed clear holistic processing, i.e., a congruency effect that was attenuated when the character parts were misaligned, while native Chinese readers, who were experts with the Chinese writing system, did not. The stronger holistic processing found in novices was interpreted as a difficulty in decomposing parts of a character due to a lack of knowledge of the Chinese writing system. Accordingly, experts did not suffer as much from such a difficulty of character decomposition and thus showed no significant holistic processing effects.

One major discrepancy between Wong, Bukach et al.'s (2011) and Hsiao and Cottrell's (2009) findings is that the holistic processing was found stronger for experts than for intermediate readers in English words (A. C.-N. Wong, Bukach et al., 2011), but Chinese experts showed smaller holistic processing with Chinese characters compared with novices (Hsiao & Cottrell, 2009). One could suggest that, because of differences in the shape of the characters and in the linguistic features of the languages involved, perception of characters in alphabetic and nonalphabetic writing systems may engage two different types of expertise. This is unlikely, however, due to the similar behavioral and neural markers of expertise for these writing systems (Gauthier et al., 2006; A. C.-N. Wong & Gauthier, 2007; A. C.-N. Wong, Gauthier et al., 2005; A. C.-N. Wong, Jobard et al., 2009). Another possibility concerns the difference in performance level between participant groups in the composite paradigm; while in A. C.-N. Wong, Bukach et al.'s (2011) study the participants were expert and intermediate English readers who had a similar performance level in the composite matching task, the Chinese novices in Hsiao and Cottrell's (2009) study had significantly worse performance in the composite matching task than experts. Moreover, there are methodological differences between the two studies. Whereas A. C.-N. Wong, Bukach et al. (2011) sequentially presented the two composites to be matched, Hsiao and Cottrell (2009) presented the composites simultaneously.

In this study we re-examined holistic processing of Chinese characters in experts and novices using the composite matching paradigm. Three characteristics of the study are worth mentioning. First, we introduced differential response deadlines for experts and novices such that both groups needed to respond with considerable time pressure and attain a similar accuracy level. This was aimed at matching performance level between the two groups and also eliminating the potential ceiling/floor effects for experts and novices such that neither group would be given a more favorable condition to show the effect.

Second, apart from comparing experts and novices, we examined the effect of experience on holistic processing by introducing both characters and noncharacters. We found before that holistic processing was larger for words than nonwords only in native English readers but not in English-as-a-second-language readers (A. C.-N. Wong, Bukach et al., 2011). Similarly, previous studies have also found the holistic processing to be larger for familiar than unfamiliar faces (Ellis, Shepherd, & Davies, 1979; Harris & Aguirre, 2008; McKone, Brewer, MacPherson, Rhodes, & Hayward, 2007; Young, Hay, McWeeny, Flude, & Ellis, 1985), for own-race than other-race faces (McKone et al., 2007; Michel, Rossion, Han, Chung, & Caldara, 2006; Mondloch et al., 2010; Rhodes, Hayward, & Winkler, 2006), and for modern than antique cars in modern car experts (Bukach et al., 2010). Based on previous findings of the effect of familiarity on holistic processing of different objects, we expected that holistic processing of characters in experts, if any, should be sensitive to the amount of experience and thus should also be higher for characters than noncharacters. Novices, however, would not show such a difference between the two character types if their main issue is the inefficiency in separating the parts of a character.

Thirdly, we adopted both sequential and simultaneous matching procedures to see if mode of presentation affects holistic processing measures. Also, while Hsiao and Cottrell (2009) used Chinese characters with a top-bottom structure (i.e., characters with two parts, one on top of the other), over 70% of frequently used compound Chinese characters have a left-right configuration (Hsiao & Shillock, 2006). We therefore examined holistic processing in both left-right and top-bottom characters in separate experiments.

Four experiments were conducted to examine the holistic processing effects for experts and novices with Chinese characters and noncharacters. Experiments 1 and 2 involved characters with a left-right structure, and Experiments 3 and 4 involved characters with a top-bottom structure. We also adopted both sequential-matching (Experiments 1 and 3) and simultaneous-matching versions (Experiments 2 and 4) of the composite task.

Experiment 1: Sequential matching of left-right characters

Method

Participants

Thirty-two Chinese readers who had Chinese as their native language were recruited at the Chinese University of Hong Kong and regarded as the expert group (12 males, mean age = 21.58). Their average language experience was 19.84 years on Chinese and 18.22 years on English. The novice group consisted of 33 native English readers at the University of Richmond with no prior experience of learning Chinese. One novice was discarded due to low accuracy (<65%), resulting in 32 participants remaining in the novice group (11 males, mean age = 18.62). All participants had normal or corrected vision and were given monetary compensation for their participation. The study was approved by the local Institutional Review Board, and informed consent was obtained in written form from all participants.

Materials

The experiment used Chinese characters and noncharacters with a left-right configuration, i.e., they can be vertically divided into two components (Figure 2A). The Chinese characters used had a mean frequency of 114 per million (*SD* = 203 per million) according to the Hong Kong Chinese Character Frequency Survey (Ho & Kwan, 2001). The noncharacters were created by swapping the position of the left and right parts of the Chinese characters. Eight sets of Chinese characters and eight sets of noncharacters were used. Each set contained four characters such that the parts could be interchanged to create the four test conditions (congruent-same, congruent-different, incongruent-same, incongruent-different; see Figure 2A). Within each set, each character appeared as the study stimulus with the same frequency; each character also appeared as the test stimulus equally often in the four different conditions.

For each participant, four sets of Chinese characters and four sets of noncharacters were used, and the selection was counterbalanced across participants. Each character or noncharacter spanned 3.2° of visual angle vertically and horizontally with a 60-cm viewing distance. The left and right halves of each stimulus were separated by a gray vertical line. In this and all other experiments, stimuli were presented on a 17-inch Mac computer using MATLAB™ (MathWorks, Natick, MA) and Psychophysics Toolbox (Brainard, 1997).

Procedure

Participants viewed a fixation cross for 500 ms and then the study stimulus for 600 ms (Figure 2C). A mask then appeared for 1300 ms, followed by the test stimulus. A cue on the left or right of the mask appeared at the last 800 ms of the mask and remained on the screen during presentation of the test stimulus. The test stimulus remained on the screen until participants responded or until the time limit. Participants had to indicate by key press ("1" for "same" and "2" for "different") if the target parts of the study and test stimuli were the same within 700 ms (for experts) and 1500 ms (for novices). These deadlines were decided based on pilot study results in order to avoid ceiling or floor effects for experts and to achieve similar general accuracy levels for experts and novices. No feedback was given. In half of the trials, the two parts of the test stimulus were misaligned by moving the noncued part vertically by about 1.6°. There were 16 trials for each of the 32 conditions (stimulus type × left/right matching × alignment × congruency × same/different response), forming a total of 512 trials divided into 16 blocks. Each of the 16 characters (four sets each with four characters) and 16 noncharacters (four sets each with four noncharacters) was presented in the study 16 times.

In all experiments, the different types of trials were randomized except that characters and noncharacters were presented using ABBA counterbalancing, with half of the participants viewing characters first and half

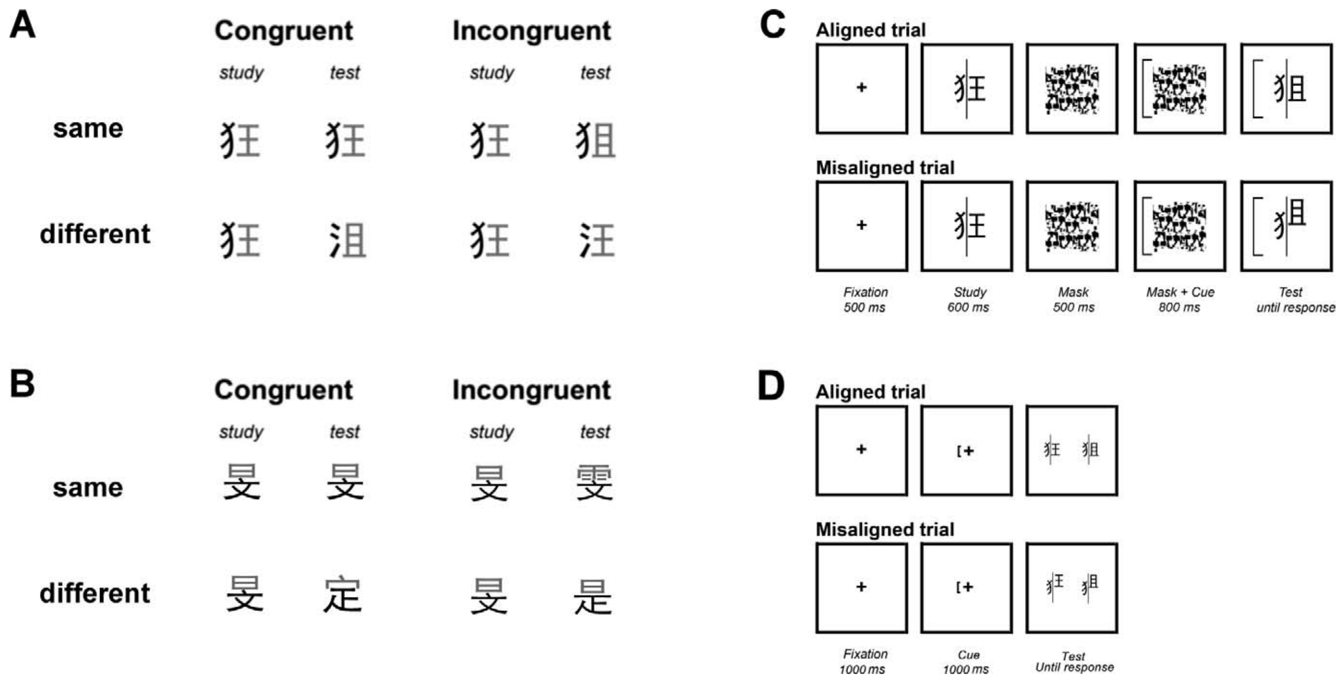

Figure 2. (A) An example set of Chinese characters with a left-right structure for Experiments 1 and 2. This assignment to conditions is for trials in which matching of the left part is required. The black parts are to be attended to while the gray parts are to be ignored (for illustration only; in the actual experiment, both parts were black). (B) An example set of characters with a top-bottom structure for Experiments 3 and 4. This assignment to conditions is for trials in which matching of the bottom part is required. (C) Trial sequence for Experiment 1, where the two composites were presented sequentially. (D) Trial sequence for Experiment 2, where the two composites were presented simultaneously. The trial sequences for Experiments 3 and 4 were the same as those for Experiments 1 and 2, respectively.

viewing noncharacters first. Participants completed 10 practice trials before the actual experimental trials began.

Data analyses

Sensitivities (A′) and response times (RT) were the dependent measures. A′ is a nonparametric measure of sensitivity according to the signal detection theory and is relatively unaffected by response bias when the assumption of normality and equal variances are violated (Stanislaw & Todorov, 1999). Since response biases existed and were not constant across conditions, A′ was preferred. A′ is computed with the following formula:

$$A' = .5 + \left[sign(H-F)\frac{(H-F)^2 + |H-F|}{4\max(H,F) - 4HF} \right]$$

where H and F represent hit rate and false alarm rate, respectively.

Following previous studies on faces, words, and characters, holistic processing effects would be indicated by (a) better performance (higher A′ and shorter RT) in the congruent than incongruent condition for the aligned trials (Bukach et al., 2010; Farah et al., 1998; Goffaux, 2009; Richler, Mack, Gauthier, & Palmeri, 2009), and (b) a larger congruency effect for aligned than misaligned trials (Bukach et al., 2010; Cheung, Richler, Palmeri, & Gauthier, 2008; Richler, Bukach, & Gauthier, 2009; A. C.-N. Wong, 2007). The second measure is typically regarded as a stronger evidence of holistic processing (Richler, Cheung, & Gauthier, 2011). The important question is whether both experts and novices would show holistic processing for characters, given the introduction of differential response deadlines to ensure similar general accuracy levels away from ceiling or floor for the two groups. Another comparison of interest would be the degree of holistic processing for characters and noncharacters, especially for experts.

Results

Sensitivities (A′) and response times (RT) for correct trials are shown in Figure 3.

Expert data

Experts with the Chinese writing system showed holistic processing for characters in both A′ and RT.

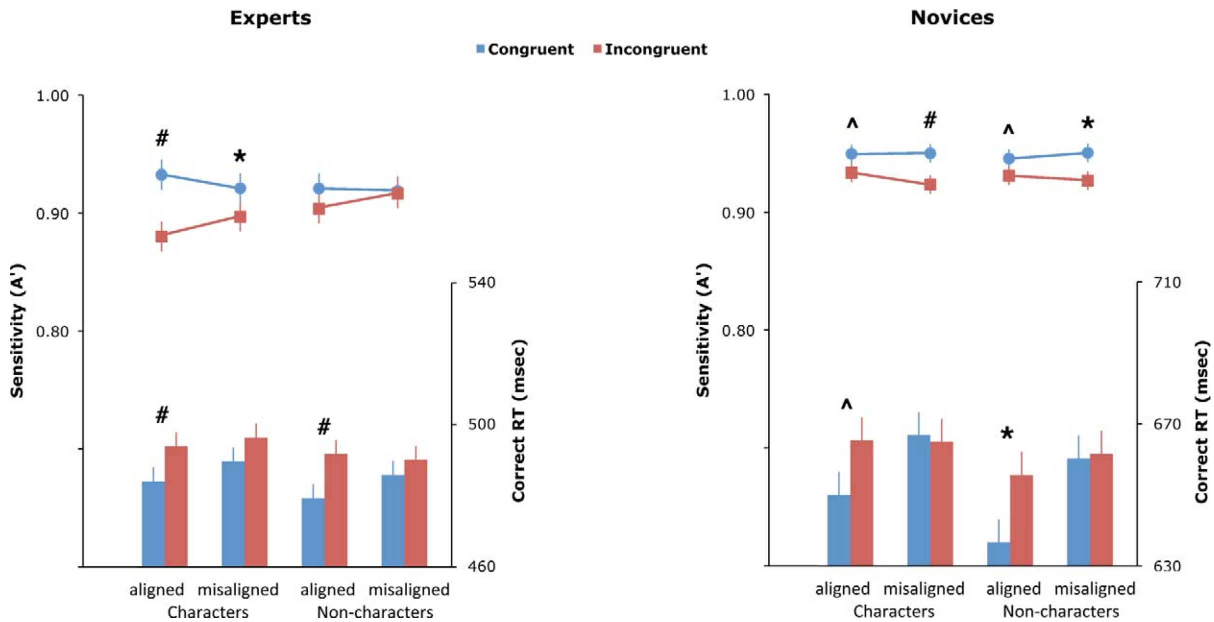

Figure 3. Results of Experiment 1. Dots represent sensitivity (A′) and bars represent response time for correct trials (Correct RT). Error bars represent 95% confidence intervals for the character type × alignment × congruency interaction. Significant differences between congruent and incongruent trials in various conditions were indicated by ˆ, *, and # (for $p < 0.05$, 0.01, and 0.001, respectively).

Responses were more accurate and faster in the congruent than incongruent condition, and this difference was larger when the two parts were aligned than misaligned. ANOVAs showed a significant congruency effect, A′: $F(1, 31) = 18.37$, $p < 0.001$, $\eta_p^2 = 0.372$; RT: $F(1, 31) = 44.83$, $p < 0.001$, $\eta_p^2 = 0.591$, as well as an alignment × congruency interaction, A′: $F(1, 31) = 5.12$, $p = 0.031$, $\eta_p^2 = 0.142$; RT: $F(1, 31) = 5.18$, $p = 0.030$, $\eta_p^2 = 0.143$. The expert congruency effect differed between characters and noncharacters in terms of A′, as indicated by the significant interaction between stimulus type and congruency, $F(1, 31) = 12.56$, $p = 0.001$, $\eta_p^2 = 0.288$. Considering the aligned trials alone, the congruency effect was also different for characters and noncharacters, $F(1, 31) = 7.879$, $p = 0.0086$, $\eta_p^2 = 0.202$, with the congruent-incongruent trial difference significant only for characters, $t(31) = 4.139$, $p = 0.002$, but not for noncharacters, $t(31) = 3.669$, $p = 0.064$. In addition, the alignment × congruency interaction only approached significance for characters, $F(1, 31) = 3.604$, $p = 0.0670$, $\eta_p^2 = 0.104$, but not for noncharacters, $F(1, 31) = 1.983$, $p = 0.1690$, although the three-way interaction between stimulus type, alignment, and congruency did not reach significance, $F < 1$.

Novice data

Novices showed holistic processing mainly in RT, with a significant effect of congruency, $F(1, 31) = 5.77$, $p = 0.022$, $\eta_p^2 = 0.157$] and an alignment × congruency interaction, $F(1, 31) = 8.12$, $p = 0.008$, $\eta_p^2 = 0.208$. In terms of A′, there was only a main effect of congruency, $F(1, 31) = 27.29$, $p < 0.001$, $\eta_p^2 = 0.468$, but it did not interact with alignment, $p > 0.18$. The effects were not different between characters and non-characters, with no significant main effect or interaction involving stimulus type, $ps > 0.214$.

Overall, both experts and novices showed holistic processing. For experts, holistic processing was larger for characters than non-characters, whereas for novices similar results were found for characters and non-characters. In Experiment 2, we adopted the same stimuli as Experiment 1 (characters with a left-right structure), yet shifted from sequential to simultaneous presentation of the study and test stimuli, in order to examine how the results in Experiment 1 generalize across paradigms.

Experiment 2: Simultaneous matching of left-right characters

Method

Participants

Similar to Experiment 1, the expert group was recruited from the Chinese University of Hong Kong and the novice group was recruited from the University of Richmond. Thirty-three Chinese readers and 34 native English readers participated for monetary compensation. One expert and two novices were discarded due to low accuracy (<65%), resulting in

32 participants remaining in the expert group (13 males, mean age = 20.9) and 32 in the novice group (11 males, mean age = 19). The average language experience of experts was 19.34 years on Chinese and 17.28 years on English.

Materials and procedure

The materials and procedure of Experiment 2 were identical to Experiment 1 with the exception that location and timing of events were adjusted for simultaneous presentation (Figure 2D). Participants viewed a fixation cross for 1000 ms. Then a cue appeared either on the left or right of the fixation for another 1000 ms, followed by two characters presented on the left and right of the fixation simultaneously until response or the response deadline. Participants had to indicate by key press ("1" for "same" and "2" for "different") if the target parts of the two characters were the same within 933 ms (for experts) and 1400 ms (for novices). Again these deadlines were decided based on the pilot study results in order to avoid ceiling or floor effects and to achieve similar general accuracy levels for experts and novices.

Results

Sensitivities (A′) and response times (RT) for correct trials are shown in Figure 4.

Expert data

Experts showed holistic processing in both A′ and RT, with better performance in the congruent than incongruent condition, especially for aligned trials. ANOVA showed a significant effects of congruency, A′: $F(1, 31) = 8.13$, $p = 0.008$, $\eta_p^2 = 0.208$; RT: $F(1, 31) = 9.42$, $p = 0.004$, $\eta_p^2 = 0.233$, and an alignment × congruency interaction, A′: $F(1, 31) = 20.31$, $p < 0.001$, $\eta_p^2 = 0.396$; RT: $F(1, 31) = 12.46$, $p = 0.001$, $\eta_p^2 = 0.287$. There was not a clear difference between characters and noncharacters. The only interaction involving stimulus type was that with congruency in A′, $F(1, 31) = 5.65$, $p = 0.024$, $\eta_p^2 = 0.154$. However, when only aligned trials were examined, there was no difference in the congruency effect for characters and noncharacters, $p > 0.388$.

Novice data

The holistic processing in novices was less conspicuous. There was a significant effect of congruency, A′: $F(1, 31) = 5.31$, $p = 0.028$, $\eta_p^2 = 0.146$; RT: $F(1, 31) = 16.33$, $p < 0.001$, $\eta_p^2 = 0.345$, but no alignment × congruency interaction or interaction involving stimulus type in both A′ and RT, $ps > 0.161$.

Similar to Experiment 1, both experts and novices showed holistic processing effects. Experts in Experiment 2, however, did not show as clear a difference between characters and non-characters as in Experiment 1. In Experiments 3 and 4, sequential and simultaneous matching of characters with a top-bottom structure will be examined.

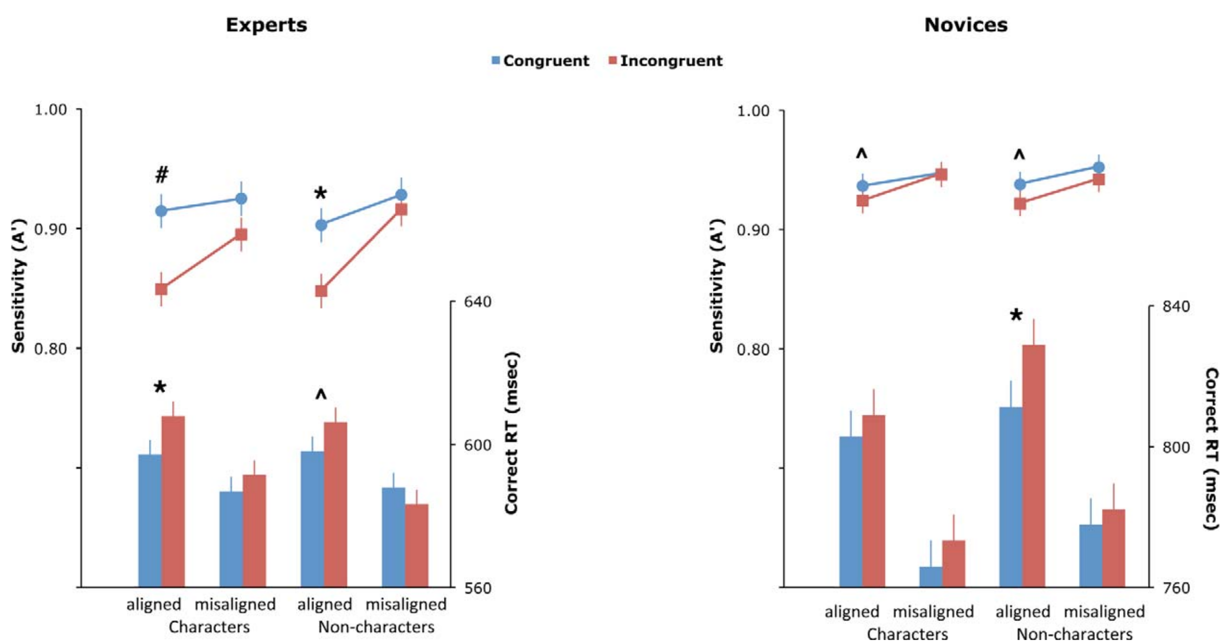

Figure 4. Results of Experiment 2. Dots represent sensitivity (A′) and bars represent response time for correct trials (Correct RT). Error bars represent 95% confidence intervals for the character type × alignment × congruency interaction. Significant differences between congruent and incongruent trials in various conditions were indicated by ˆ, *, and # (for $p < 0.05$, 0.01, and 0.001, respectively).

Experiment 3: Sequential matching of top-bottom characters

Method

Participants

Forty-one Chinese readers and 35 native English readers participated for monetary compensation. Nine expert and three novices were discarded due to low accuracy (<65%), resulting in 32 participants remaining in the expert group (15 males, mean age = 21.16) and 32 in the novice group (6 males, mean age = 19.09). The average language experience of experts was 19.34 years on Chinese and 17.5 years on English.

Materials

The experiment used Chinese characters and noncharacters in a top-bottom configuration, i.e., each of them can be divided by a horizontal line into two components (Figure 2B). Eighty pairs of Chinese characters and 80 pairs of noncharacters were used. The characters chosen and their assignment to different conditions were the same as those used in Hsiao and Cottrell (2009): 20 of the 80 character pairs were assigned to each of the four conditions (congruent-same, congruent-different, incongruent-same, incongruent-different), and the characters in the congruent and incongruent conditions did not differ in their frequency. The noncharacters were generated by rearranging the top and bottom parts of the characters used. Each character or noncharacter spanned 1.5° of visual angle vertically and horizontally with a 60-cm viewing distance. The top and bottom halves of each stimulus were separated by a gray horizontal line.

Procedure

The procedure was identical to that of Experiment 1, except that the characters used were of top-bottom configuration instead of left-right configuration. Consequently, the cue following the mask was on the top or bottom of the mask, indicating which half of the character the participant should match. In half of the trials, the two parts of the test stimulus were misaligned by moving the noncued part horizontally by 0.8°. There were 10 trials for each of the 32 conditions (stimulus type × top/bottom matching × alignment × congruency × same/different response), forming a total of 320 trials divided into eight blocks.

Results

Sensitivities (A′) and response times (RT) for correct trials are shown in Figure 5.

Expert data

Experts showed holistic processing for both characters and noncharacters. Performance was better in congruent than incongruent trials, although only for characters did the congruency effect seem to depend on alignment in RT. ANOVAs showed a significant congruency effect, A′: $F(1, 31) = 43.73$, $p < 0.001$, $\eta_p^2 = 0.585$; RT: $F(1, 31) = 10.96$, $p = 0.002$, $\eta_p^2 = 0.261$. In addition, RT data showed a stimulus type × alignment × congruency interaction that was close to significant, $F(1, 31) = 3.067$, $p = 0.090$, $\eta_p^2 = 0.090$, due to a significant Alignment × congruency interaction for characters only, $F(1, 31) = 5.677$, $p = 0.023$, $\eta_p^2 = 0.154$, but not for noncharacters, $F < 1$.

Novice data

Holistic processing in novices was indicated by a significant congruency effect in A′, $F(1, 31) = 34.35$, $p < 0.001$, $\eta_p^2 = 0.526$, and a significant alignment × congruency interaction, A′: $F(1, 31) = 7.50$, $p = 0.010$, $\eta_p^2 = 0.195$; RT: $F(1, 31) = 12.281$, $p = 0.001$, $\eta_p^2 = 0.284$. Surprisingly, holistic processing seemed larger for noncharacters than characters in terms of A′. The stimulus type × congruency interaction was close to significant, $F(1, 31) = 3.74$, $p = 0.062$, $\eta_p^2 = 0.108$. When only aligned trials were considered, the congruency effect was found to be larger for noncharacters than characters, $F(1, 31) = 5.876$, $p = 0.021$, $\eta_p^2 = 0.159$.

Despite the different stimuli used (characters with a top-bottom configuration) compared with Experiments 1 and 2, again in Experiment 3 both experts and novices displayed holistic processing. Whereas experts showed larger holistic processing for characters than noncharacters, novices showed the opposite pattern.

Experiment 4: Simultaneous matching of top-bottom characters

Method

Participants

Thirty-five Chinese readers and 34 native English readers participated for monetary compensation. Three expert and two novices were discarded due to low accuracy (<65%), resulting in 32 participants remain-

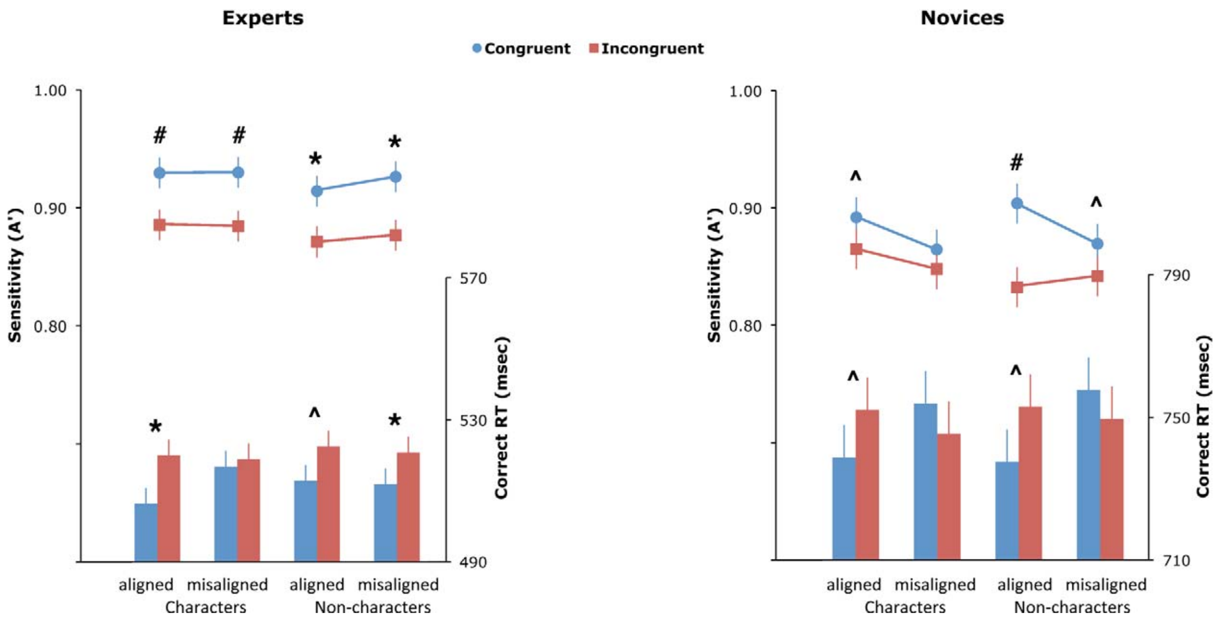

Figure 5. Results of Experiment 3. Dots represent sensitivity (A′) and bars represent response time for correct trials (Correct RT). Error bars represent 95% confidence intervals for the character type × alignment × congruency interaction. Significant differences between congruent and incongruent trials in various conditions were indicated by ˆ, *, and # (for $p < 0.05$, 0.01, and 0.001, respectively).

ing in the expert group (10 males, mean age = 20.13) and 32 in the novice group (13 males, mean age = 19.06). The average language experience of experts was 17.97 years on Chinese and 16.13 years on English.

Materials and procedure

The materials and procedure of Experiment 4 were identical to those used in Experiment 3, with the exception that the stimuli location and durations were identical to those used for simultaneous presentation in Experiment 2.

Results

Sensitivities (A′) and response times (RT) for correct trials are shown in Figure 6.

Expert data

Holistic processing in experts was indicated by the significant congruency effect, A′: $F(1, 31) = 68.40$, $p < 0.001$, $\eta_p^2 = 0.688$; RT: $F(1, 31) = 40.808$, $p < 0.001$, $\eta_p^2 = 0.568$, as well as alignment × congruency interaction, A′: $F(1, 31) = 9.350$, $p = 0.005$, $\eta_p^2 = 0.232$; RT: $F(1, 31) = 2.91$, $p = 0.098$, $\eta_p^2 = 0.086$. In terms of RT, holistic processing seemed to be larger for characters and noncharacters. The stimulus type × alignment × congruency interaction was close to significant, $F(1, 31) = 2.91$, $p = 0.098$, $\eta_p^2 = 0.086$, due to the fact that the congruency effect depended on alignment only for characters, $F(1, 31) = 13.35$, $p < 0.001$, $\eta_p^2 = 0.301$, but not for noncharacters, $p > 0.22$.

Novice data

Holistic processing for novices was reflected by a significant congruency effect, A′: $F(1, 31) = 58.76$, $p < 0.001$, $\eta_p^2 = 0.655$; RT: $F(1, 31) = 61.50$, $p < 0.001$, $\eta_p^2 = 0.665$, and an alignment × congruency interaction, A′: $F(1, 62) = 2.99$, $p = 0.094$, $\eta_p^2 = 0.088$; RT: $F(1, 31) = 8.21$, $p = 0.007$, $\eta_p^2 = 0.209$. In addition, RT showed larger holistic processing for noncharacters, as indicated by a significant stimulus type × congruency interaction, $F(1, 31) = 13.73$, $p = 0.001$, $\eta_p^2 = 0.307$. When only the aligned trials were considered, the congruency effect was also larger for noncharacters than characters, $F(1, 31) = 5.90$, $p = 0.021$, $\eta_p^2 = 0.159$.

Overall, results of Experiment 4 were very similar to those in Experiment 3. Experts showed larger holistic processing for characters than noncharacters, whereas novices showed larger holistic processing for noncharacters.

General discussion

In four experiments, we consistently observed holistic processing for both experts and novices with the Chinese writing system when they had a similar performance level in the composite matching task. The results were found for both characters with a left-right

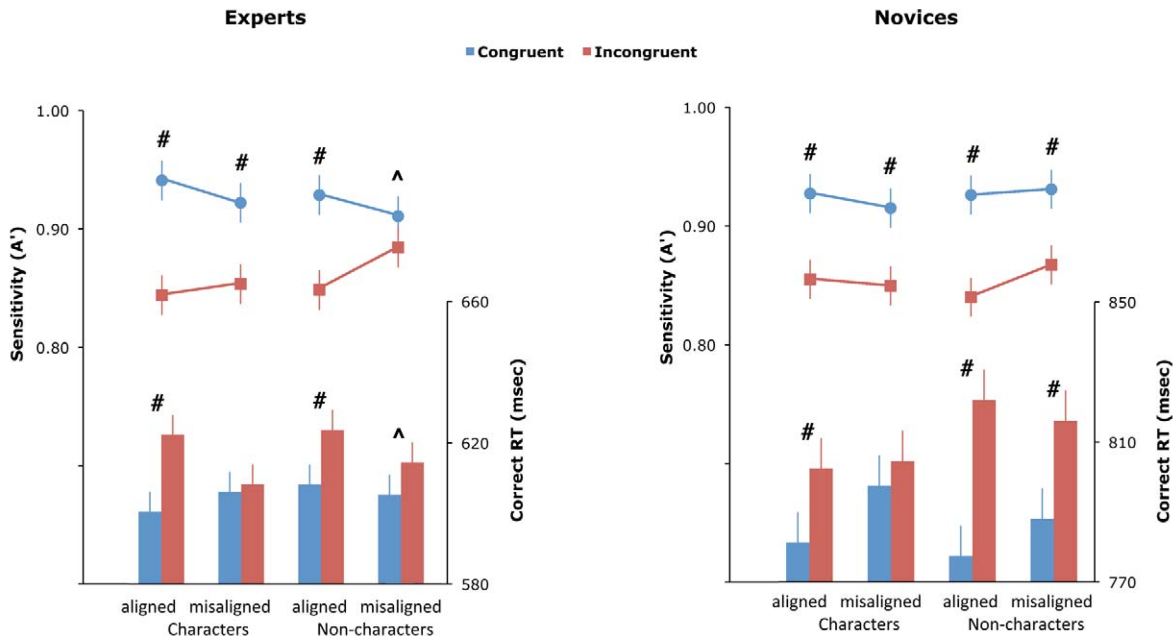

Figure 6. Results of Experiment 4. Dots represent sensitivity (A′) and bars represent response time for correct trials (Correct RT). Error bars represent 95% confidence intervals for the character type × alignment × congruency interaction. Significant differences between congruent and incongruent trials in various conditions were indicated by ˆ, *, and # (for $p < 0.05$, 0.01, and 0.001, respectively).

and top-bottom structure and for both sequential and simultaneous matching paradigms. This was in contrast to Hsiao and Cottrell's (2009) findings, where experts had significantly better performance than novices and holistic processing was found for novices only, not experts. The introduction of differential response deadlines for experts and novices was likely the key here: While in Hsiao and Cottrell (2009) experts' performance was around a level of $A' = 0.95$ and novices' performance was around $A' = 0.87$ without using differential response deadlines, in the current study A′ was kept below 0.95 in most conditions for both groups. When the experts were not susceptible to the ceiling effects, they also revealed robust holistic processing regardless of the character structure or the presentation paradigm.

Our findings also suggest that holistic processing develops as one acquires expertise with characters in a writing system. Although both experts and novices showed holistic processing, the use of characters and noncharacters helped to dissociate the effects in these two groups (Table 1). Experts displayed a trend of larger holistic processing for characters than noncharacters in three out of four experiments. This is consistent with the findings for English words in A. C.-N. Wong, Bukach et al. (2011). The experts in the current study were recruited from the same population as the English-as-a-second-language readers in A. C.-N. Wong, Bukach et al. (2011): They were bilinguals in Hong Kong with Chinese as their native language and English as the second language. These individuals showed holistic processing for Chinese characters (current study) and English words (A. C.-N. Wong, Bukach et al., 2011), but only with Chinese characters was their holistic processing effect sensitive to experience (i.e., larger for characters than noncharacters). Therefore, just like perception of faces and other objects involving fine-detailed, subordinate-level discrimination, acquisition of expertise in perception of texts like English words and Chinese characters also involves the development of holistic processing associated with familiarity with the stimuli.

Novices, however, did not show larger holistic processing for characters like experts. The Chinese novices in our current study were also drawn from the same population as the native English readers in A. C.-N. Wong, Bukach et al. (2011): They were American undergraduate students with English as their native language and with little experience in learning Chinese. These individuals showed holistic processing with English words and Chinese characters, but only that for English words was sensitive to the experience with words (i.e., larger for words than nonwords). Their result pattern is consistent with Hsiao and Cottrell's (2009) suggestion that novices lack understanding of the structures of characters and therefore find it hard to separate a character-like pattern into its parts and selectively attend to one of them. One may wonder, however, why novices showed more holistic processing for noncharacters in Experiments 3 and 4, in which top-bottom characters were used. We speculate that the difference found in Experiments 3 and 4 does not

Experiment			Experts	Novices
1	Left-right characters	Sequential	Congruency effect in aligned trials and alignment × congruency interaction (both in A′) significant for characters but not for noncharacters	—
2	Left-right characters	Simultaneous	—	—
3	Top-bottom characters	Sequential	Alignment × congruency interaction (RT) significant for characters but not for noncharacters	Congruency effect in aligned trials (A′) significant for both character types yet larger for noncharacters
4	Top-bottom characters	Simultaneous	Alignment × congruency interaction (RT) significant for characters but not for noncharacters	Congruency effect in aligned trials (RT) significant for both character types yet larger for noncharacters

Table 1. A summary of the differences in holistic processing effects between characters and noncharacters for experts and novices in the four experiments.

represent true difference between characters and noncharacters in general. Instead it could be a result of the appearance of noncharacters used in these two experiments. Examination of the stimuli revealed that the noncharacters were more variable in terms of length, possibly leading to more confusion over the boundary between the top and bottom parts. This might lead to larger difficulty separating the parts, and thus more interference from irrelevant parts and larger holistic processing. Such an issue does not exist for the left-right characters in the first two experiments, in which noncharacters were formed by swapping the left and right parts of a character and thus the size of the two character types was the same.

There are a number of similarities between the holistic processing found for characters in the current study and that found for faces and other domains of expertise. For example, holistic face processing, like that for characters, has been found for both sequential and simultaneous matching of the study and test stimuli (Richler, Tanaka et al., 2008; Robbins & McKone, 2007). Also, as discussed before, holistic processing of faces and cars was larger for familiar than unfamiliar stimuli (Bukach et al., 2010; Ellis et al., 1979; Harris & Aguirre, 2008; Young et al., 1985), just like the larger holistic processing for words/characters than nonwords/noncharacters. As face expertise has been much more extensively studied than that for words and characters, it remains to be seen if some of the characteristics of holistic face processing can also be observed for words and characters. For example, holistic face processing tends to be unaffected within a broad range of presentation times of the study and test stimuli (Richler, Mack et al., 2009; Richler, Mack, Palmeri, & Gauthier, 2011); generalizes across different recognition demands, e.g., recognition based on identity (Richler, Tanaka et al., 2008), gender (Zhao & Hayward, 2010), and emotional expressions (Calder, Keane, Young, & Dean, 2000); and predicts recognition performance (Richler, Cheung et al., 2011). Yet it differs among individuals with different types of expertise with faces, e.g., artists with ample face drawing experience versus normal observers (Zhou, Cheng, Zhang, & Wong, 2012), and within the same individual under different states, e.g., positive versus negative moods (Curby, Johnson, & Tyson, 2012). More extensive studies of holistic processing of words and characters would allow better comparison with holistic processing of faces and other objects.

Despite the similarities between holistic processing of words and faces discussed above, differences in neural selectivity and higher level processing between texts and faces make it likely that the nature and temporal dynamics of holistic processing would be different between the two domains. Therefore, the requirement of fine-detailed discrimination that may account for the development of holistic face processing (Bukach, Gauthier, & Tarr, 2006; A. C.-N. Wong & Palmeri et al., 2009) may not apply to words and characters. Instead, it could be due to the fact that visual processing of words and characters provides output to linguistic processing and writing. As an interface for communication with other modalities, orthographic representations comprising multiple letters or components or even a whole word or character could be the entry point of recognition of text, leading to obligatory attention to multiple components of a word or character (Chan et al., 2009; Dehaene, Cohen, Sigman, & Vinckier, 2005; James, Wong, & Jobard, 2009).

A characteristic particularly worth discussing about the current study is the finding of holistic processing of characters for both experts and novices. Interestingly, it resonates with a recent study of the holistic processing of musical notes (Y. K. Wong & Gauthier, 2010), in which both musicians and nonmusicians showed a congruency effect, but for different reasons. By manipulating the target position within a note sequence, it was shown that expert holistic processing reflected automatic allocation of attention to all notes in a sequence, whereas novice holistic processing was caused by their strategy in fulfilling the task demand given their inefficiency in processing all the notes at the same time. A common theme tying together the studies of words/characters and musical notes is that, while novices show holistic processing due to inefficiency in processing an unfamiliar stimulus, expert holistic processing is a result of the change in the way attention is allocated to a stimulus of expertise. Studying the modulation of holistic processing effects by different factors may therefore be important for revealing the mechanisms that support the effects (Richler, Wong, & Gauthier, 2011).

As suggested by comparing holistic processing across domains, even though the same composite paradigm was used to reveal holistic processing for words and characters and that for faces and other objects of subordinate-level expertise, it does not necessarily mean that the effects were caused by similar underlying mechanisms. One obvious way to pursue the question is to probe the neural correlates of holistic processing. While holistic face processing has been linked with the N170 component in event-related potential (ERP) studies (Jacques & Rossion, 2009; Kuefner, Jacques, Prieto, & Rossion, 2010; Letourneau & Mitchell, 2008), the locus of holistic processing of words and characters remain to be seen. Behavioral and computational attempts have also been made to tease apart the perceptual and decisional contributions to the holistic processing effects (Mack, Richler, Gauthier, & Palmeri, 2011; Richler, Cheung, Wong, & Gauthier, 2009; Richler, Gauthier, Wenger, & Palmeri, 2008). Other decision-making models, like the general context model (GCM) and its variants (Lamberts, 2000; Nosofsky & Palmeri, 1997), the linear ballistic accumulator (LBA) model (Brown & Heathcote, 2008) and the diffusion model (Vandekerckhove & Tuerlinckx, 2007), are capable of describing changes in different phases of processing as a result of experience. It is thus expected that more sophisticated experimental design and data analysis tools, together with the neural studies, can be very fruitful means of understanding the locus of holistic processing. Another potential avenue is to tease apart the contribution of visual, semantic, and motor factors to holistic processing by comparing novel character training paradigms that focus on one of these aspects.

Up to now, holistic processing has been found for expertise in various object categories, suggesting its potential to be a good general marker of perceptual expertise with objects. It is sometimes necessary, however, to examine the effect in different situations, in order to tease apart effects in experts and novices. When print is concerned (e.g., English words, and Chinese characters), manipulating word or character type has been shown to be useful for singling out expertise-associated holistic processing. The current study focused on one aspect of holistic processing – the obligatory attention to all parts of an object. Whether other aspects of holistic processing (e.g., sensitivity to detailed spatial information) exist for processing of characters and words would require further investigation.

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