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Categorical perception of Chinese characters by simplified and traditional Chinese readers

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Abstract Recent research has shown that the visual complexity of orthographies across writing systems influences the development of orthographic representations. Simplified and traditional Chinese characters are usually regarded as the most visually complicated writing systems currently in use, with the traditional system showing a higher level of complexity. However, it is still unclear whether and how learning two Chinese writing systems influences the processing of characters among simplified and traditional Chinese script readers. This study employed the categorical perception (CP) paradigm to examine adult Mainland China Chinese (MLC) simplified character readers and adult Hong Kong Chinese (HKC) traditional character readers' liminal perception of the following types of morphing continua of "line characters" (with font features removed): the Absolute-Differentiation (AD) type, which contains a topological change, and the Relative-Differentiation type, which does not contain any topological change in visual configurations. The results showed evidence of CP effects on the two types of stimuli among MLC and HKC readers. Moreover, MLC and HKC readers presented major differences in perceiving AD-type stimuli, indicating that different experiences with two Chinese writing systems influence character perception. These findings extend previous results regarding the comparison of visual skills of simplified and traditional Chinese script readers and support the hypothesis that simplified Chinese script readers have higher visual discrimination rates than do traditional Chinese script readers in character perception.

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Introduction

Successful reading requires effectively mapping visual symbols of a writing system to its corresponding oral language. The majority of previous reading studies across writing systems have uncovered and highlighted the importance of principles governing how writing units (i.e., graphemes) map to various linguistic units such as phonemes, syllables and morphemes (Wang & Tsai, 2011). However, although recent studies have begun to tackle the relationship between visual skills and learning to read across writing systems, relatively less attention has been paid to how the visual-orthographic properties of various writing systems interact with reading development and processing among different groups of readers (such as children, adult experts and cohorts with reading disabilities).

Specifically concerning Chinese reading, two Chinese writing systems are widely used across Chinese societies, with simplified characters mainly used in Mainland China, Singapore and Malaysia, and traditional characters mainly used in Hong Kong, Taiwan and Macau. The present study is primarily concerned with Mainland China Chinese (MLC hereafter) readers and Hong Kong Chinese (HKC hereafter) readers. Historically, simplified characters have been implemented through the Chinese writing reform in Mainland China from 1950s and have been widely used for more than 60 years, while simultaneously, traditional characters are continuously used in Hong Kong. Moreover, due to the complexity of teaching and learning strategies, fluency levels of character usage, influences from concurrently used spoken languages and writing systems, and other social environmental factors (such as the popularity of computers and other electronic devices) among the two groups of character users, HKC and MLC readers' visual skills and their orthographic knowledge of characters may have been shaped differently in depth at both behavioral and neurobiological levels.

Even though some recent studies have begun to show the important association of visual skills and Chinese reading development (e.g., McBride, Chow, Zhong, Burgess, & Hayward, 2005; McBride et al., 2011; Peng, Minett, & Wang, 2010a), few previous studies on Chinese reading have attempted to further confirm and explain the cultural variability in the two Chinese writing systems, instead emphasizing the more universal aspects of reading in Chinese. How long-term experience with traditional and simplified characters shapes HKC and MLC readers' character processing and visual skills remains unclear. Therefore, the central research question addressed in present study is as follows: Does long-term experience with traditional or simplified characters influence adult HKC and MLC readers' respective perception of characters? To tackle this question, we used the classical categorical perception paradigm and considered the connection and comparability of phonemes in spoken language and graphemes in written language.

Visual-orthographic and topological properties of Chinese characters and visual skills in reading Chinese

Simplified and traditional characters differ at several levels but most importantly in their visual-orthographic properties. As fundamental units of Chinese orthography, each character is built of several strokes, which can be combined to form a higher unit, sub-lexical components of characters. One approach to explain character processing focuses on a purely structural view, the primary concern of which is on the constructional roles of sub-lexical components serving as input units to the whole character (e.g., Chen, Allport, & Marshall, 1996; Taft, 2006). The starting point of this approach is based on an assumption that there is a unit that represents the whole character and that this unit is activated via a set of relevant graphic features that match with those that are extracted from the visually presented characters.

The perception of characters is therefore a type of object perception and requires general visual skills. Tzeng and Wang (1983) noted that reading Chinese characters requires larger involvement of visual processing and memory than reading alphabetic scripts. Some other studies also explored the effect of visual-spatial properties on character recognition and considered the visual configuration properties of characters. Ai (1955) suggested that characters with symmetric, closed, and linear (horizontal and/or vertical lines) features or with less than ten strokes were recognized more easily than those with other configurations. Later, Kao (2000) developed a psycho-geometrical theory of reading and writing characters, which suggested that characters with balance, closure, holes, linearity, center of gravity, orientation, connectivity, symmetry, and parallelism should be recognized and learned faster and easier. Gao and Kao (2002) further suggested that some visual-spatial patterns in characters were more salient or important than others, and these patterns closely conformed to basic topological perception of human vision.

Generally, topology is a branch of mathematics that aims to study invariant properties and relationships under continuous and one-to-one transformations. The properties preserved under an arbitrary topological transformation are called topological properties. Connectivity, hole and closure are typical topological properties, which are invariant under continuous and one-to-one transformations (Chen, 1982, 2005). Take the solid square "■", the solid disk "●" and the ring "○" for example; the former two share the same topological properties from the viewpoint of topology, and they are topologically different with the ring due to the "hole" property of the ring. According to Chen (1982, 1985, 2005) and Todd, Chen, and Norman (1998), a primitive general function of the visual system is the perception of global topological properties, and the relative perceptual salience of object properties may be systematically related to their structural stability under change. Connecting with characters, a character can be seen to portray an imaginary or visible rigid square, which is a perfect geometric pattern because it incorporates typical topological properties, connectivity, closure, and hole. Particularly, most characters are topologically different although they may share similar configurations, such as "申" and "甲", in which the middle vertical stroke crosses the horizontal part of the second stroke "ㄱ" in "申" and makes it topologically different from "甲". In contrast, some characters are topologically the same, such as "末" and "未", in which the two horizontal strokes change in lengths but never connect with each other. However, the number of such characters is quite limited. In the current study, the above two types of characters will be further explained in the Stimulus section. In addition, Chen and Kao (2002) reported that visual-spatial properties inherent in characters could be used quickly enough to provide a perceptual basis for orthographic processing of characters, but very few studies have examined the role of topological properties in character perception, especially considering different script experiences.

We acquire written languages through learning to read and write. Normal readers can become experts of a writing system after systematic training, and polish their skills in usage of this system across their lifespan. Even though reading requires forming an effective connection of visual symbols with language circuits in our brain, the visual-orthographic knowledge of writing systems is the critical stage to access this connection. Some previous studies began to show that different visual complexities of the orthographic structure of writing systems substantially influenced reading development and reading processes (Abdelhadi, Ibrahim, & Eviatar, 2011; Chang, Plaut, & Perfetti, 2016; McBride et al., 2011; Peng et al., 2010a; Tamaoka & Kiyama, 2013; Tan, Spinks, Eden, Perfetti, & Siok, 2005; Tzeng & Wang, 1983). Moreover, Dehaene et al. (2010) measured brain responses of adult readers with variable literacy (illiterate, becoming literate in adulthood and becoming literate in childhood) through functional magnetic resonance imaging (fMRI) when they were presented with spoken-language stimuli, written-language stimuli, visual faces, houses, tools and checkers. They found that literacy education occurring in both childhood and adulthood can profoundly refine readers' cortical organization at different levels, indicating that the effect of different literacy acquisition experiences can persist and be detected even in adulthood (see also Dehaene, Cohen, Morais, & Kolinsky, 2015).

For Chinese reading, Cheung and Ng (2003) compared Chinese reading development in four major Chinese societies (Hong Kong, Mainland China, Taiwan and Singapore) and suggested that reading development in childhood was subject to several socio-psycho-linguistic factors, including script differences. McBride (2004, 2015, 2016), Zhang and McBride (2011) and McBride and Wang (2015) also reviewed the wide diversity of Chinese learning environments for Chinese literacy development, and emphasized particularly that the diversity was highly related to the difference in traditional and simplified scripts taught and used in Chinese societies, which may induce relative benefits and difficulties when using them. Therefore, these studies suggested that Chinese literacy development needs extensive research at multiple levels and special attention must be paid to the impacts of learning traditional and simplified characters.

Despite relatively small numbers of research on visual-orthographic predictors of Chinese literacy development, several studies started to provide possible answers to the impact of experience with simplified and traditional characters. Chen and Yuen (1991) compared children from Mainland China, Hong Kong, and Taiwan, and found that MLC children's learning experience with simplified characters probably made them more responsive to visual information from characters and use it for character identification. Hoosain (1991) also suggested that visual abilities and reading skills should be bi-directionally associated, and thus learning to read might improve certain visual skills in literates. Later, McBride et al. (2005) found that the visual skills of MLC children learning simplified characters were significantly higher than those of HKC children learning traditional script. A further study by McBride et al. (2011) reported that HKC and Korean kindergarteners significantly outperformed Israeli and Spanish peers on a task of visual-spatial skills. Neurobiologically, Peng et al. (2010a) conducted an event-related potential (ERP) experiment and reported that adult MLC participants who learned simplified characters showed significantly larger P300 amplitude in the real-character condition than in the non-character condition, while HKC participants with traditional character experience did not show a significant difference. To summarize, even under limited attention, studies reviewed above already began to uncover the potential effect of learning simplified and traditional characters in shaping Chinese readers' visual skills and their orthographic knowledge on processing characters, indicating a group level traditional-simplified-Chinese-script effect, but the findings are still inconclusive.

Categorical perception

Categorical perception (CP) refers to a phenomenon that a range of stimuli from a physical continuum give rise to a limited set of discrete perceptual responses (Pastore, 1987). When categories are formed, there is a relative perceptual change on category boundary by enlarging the perceptual distance of the category boundary while shrinking the perceptual distance within a category. CP was thought to be peculiar to adult speech, but it turns out to be a much more general phenomenon that has been reported in human color perception, infant studies and animal experiments (Harnad, 1987). It is also assumed that CP effects are due to perceptual processes at the psychophysical level, but these low-level perceptual effects may be indicative of general cognitive processes in high-level conceptual systems (Goldstone & Hendrickson, 2010; Zhang, 2016). In one of the earliest examples of CP effects, Liberman, Harris, Hoffman, & Griffith (1957) studied perception of phoneme categories of stop-consonants, which differed in their place of articulation (i.e., /ba/, /da/ and /ga/). In this study, when participants were presented with equally spaced stimulus pairs, they discriminated pairs that crossed phoneme boundaries the easiest. After this preliminary research, in the domain of human speech, the CP phenomenon has also been discussed in several studies on perception of vowels (e.g., Fry, Abramson, Eimas, & Liberman, 1962) and tones (Abramson, 1979; Francis, Ciocca, & Ng, 2003; Wang, 1976). In addition to speech, in the visual modality, CP effects are also reported in perception of colors (e.g., Gilbert, Regier, Kay, & Ivry, 2006; Harnad, 1987), facial expressions (e.g., Etcoff & Magee, 1992) and individual faces (e.g., Beale & Keil, 1995). Several later studies also reported that CP effects are influenced by long-term experience with different types of categorical representations, such as experiences with tone language and non-tone language (Hallé, Chang, & Best, 2004), and tone language experience with different tone inventories (Peng et al., 2010b; Zheng, Minett, Peng, & Wang, 2011). Therefore, there are two long-standing critically unresolved questions in CP studies. The first is whether the CP effects found in speech perception could also be found in other domains. The second is about the role of learning experience in shaping categories in different domains.

Given that CP effects can be observed in both the auditory and visual modalities with various types of stimuli and can be shaped by experiences, it thus becomes natural to ask whether CP effects can be observed in perceiving writing units, i.e., the grapheme categories, which are also closely related to oral language. However, to our knowledge, with the exception of an early study by Yasuhara and Kuklinski (1978) in which CP effects were observed in both real-letter and non-letter continua, research has rarely explored this issue, i.e., CP effects in grapheme perception, particularly considering characters as stimuli and incorporating the factor of traditional and simplified Chinese script experience.

The present study

In Peng et al. (2010a), they recruited adult MLC and HKC readers, and showed that only MLC readers could differentiate stimuli based on their linguistic functions (real-characters and non-characters) and physical properties (high-symmetry characters and low-symmetry characters) at the level of liminal perception as indexed by P300 amplitude. The concept of differentiating linguistic functions and physical properties in perceiving characters in the study of Peng et al. (2010a) corresponded to questions raised in CP studies of spoken-language units, that is, how functional properties (i.e., consonants, vowels or tones can be shaped by specific language experiences and can/cannot differentiate meaning in specific languages) and physical properties (i.e., acoustic properties of a sound that can be manipulated experimentally) influence the CP pattern of specific spoken-language units. However, compared with CP studies in spoken language, the study of Peng et al. (2010a) did not directly manipulate the linear change in characters and therefore did not provided a sufficient picture on how functional and physical properties should be defined in written language, how they influence perception of characters, or how they interact with the written-language experience of Chinese readers. To tackle these questions, we employed a CP paradigm to manipulate characters linearly and further examine the CP effects of character perception and ask more specific questions about whether and how long-term experience with simplified and traditional characters shapes the CP effects in perceiving characters. In particular, as mentioned above, compared with the phoneme distinction in spoken-language perception, there are some characters that form "minimal pairs (i.e., graphemes)" in Chinese writing units, such as "申 versus 甲" and "末 versus 未", which allows us to manipulate their functional (i.e., characters in each above pair have different meanings related to orthographic knowledge) and physical (i.e., visual graphic forms) properties linearly.

Therefore, in the current experiment, we perform the following experiments: (a) observe the CP effects in character perception by MLC and HKC readers and (b) observe a group-level difference in CP effects in MLC and HKC readers.

Specifically, with the CP paradigm, we expect to observe different identification and discrimination scores for MLC and HKC readers.

Methodolody

Participants

Twenty-two MLC undergraduate students (13 females; 9 males; mean age = 20.5, SD = 1.4) from Peking University (PKU) and The Chinese University of Hong Kong (CUHK), and 20 HKC undergraduate students (10 females; 10 males; mean age = 20.7, SD = 1.0) from CUHK participated in this experiment. All MLC participants are native Mandarin speakers who grew up and obtained their elementary and secondary school education in Mainland China; all HKC participants are native Cantonese speakers who grew up and obtained their elementary and secondary school education in Hong Kong. These two groups of participants were similar in age and years of formal education. Except for one MLC participant who failed to complete the experiment due to fatigue, all other participants are right-handed according to Edinburgh Handedness Inventory (Oldfield, 1971), have normal or corrected-to-normal vision and are not color-blind. All participants were paid for their participation and provided informed consent in compliance with a protocol approved by the Survey and Behavioral Research Ethics Committee of PKU and CUHK.

Stimuli

According to the CP paradigm we employed, we constructed stimuli based on two groups of Chinese characters, which we distinguished into the following types: (1) an *Absolute-Differentiation* (AD) type, including "申-甲" and "由-田" ("申, /shen1/, express"; "甲, /jia3/, first"; "由, /you2/, reason"; 田, /tian2/, farmland"), and (2) a *Relative-Differentiation* (RD) type, including "末-未" and "士-土" ("末, /mo4/, end"; "未, /wei4/, not yet"; "士, /shi4/, scholar; "土, /tu3/, soil"). The occurrence of frequencies (per million) of the AD and RD stimuli between simple (MLC) and traditional (HKC) characters are reported in Table 1 and were collected from a

Table 1 Word frequency (per million) of AD and RD stimuli (SEM: standard error of means)

AD	Frequency		*RD*	Frequency	
	HKC	MLC		HKC	MLC
申	143	51	末	84	95
甲	51	59	未	871	427
由	1691	1172	士	925	299
田	148	207	土	250	1085
Mean	508.3	372.3	Mean	532.5	476.5
SEM	394.9	269.0	SEM	214.0	214.0

CUHK online corpus (Ho & Kwan, 2001) with its 80s-to-90s data. Simple *t*-tests show that the word frequency of the AD and RD stimuli between simple (MLC) and traditional (HKC) characters was not significantly different, $p > 0.1$.

The specific meanings of AD and RD will be given in paragraphs below. With visual feature variation in the fonts deleted, we called the two types of characters the “line characters (線字)”. Four pairs of them were constructed as fundamental stimuli for further manipulation, as shown in Fig. 1.

Given that Chen (1982, 2005) reported that the human visual system is sensitive to global topological properties of objects and suggested that a primitive general function of the visual system may be the perception of global topological properties, we defined and differentiated the two groups of “line characters” specifically according to the concept of topological properties. As stated previously, connectivity, hole and closure are the typical topological properties, which are invariant under continuous and one-to-one transformations. Comparably, topological properties change differently in AD and RD groups of continua. Specifically, for the *AD group*, its topological pattern changes along the continuum, i.e., at least two topological properties, the closure and connectivity, change from “申” to “甲” and from “由” to “田”. In contrast, in the *RD group*, no matter how the relative lengths of the two horizontal strokes change in “末-未” and “士-土”, there is no qualitative change in their topological properties. In other words, at the level of visual perception (reflecting physical properties), the two types of stimuli were differentiated in their topological properties. Simultaneously, at the level of orthographic knowledge (reflecting functional properties), the two types of stimuli also incorporated stroke change among different real characters and different meanings. Therefore, the current design can help to examine the impacts of experience with the two different Chinese writing systems at both the visual perception level and the orthographic knowledge level.

Hence, 4 sets of 11-step continua were constructed based on the AD-type and RD-type line characters, as shown in Fig. 2. These stimuli were generated along the linear continua by using a “morph” program (Sqirlz Morph 2.1, ref. Jones, 2009).

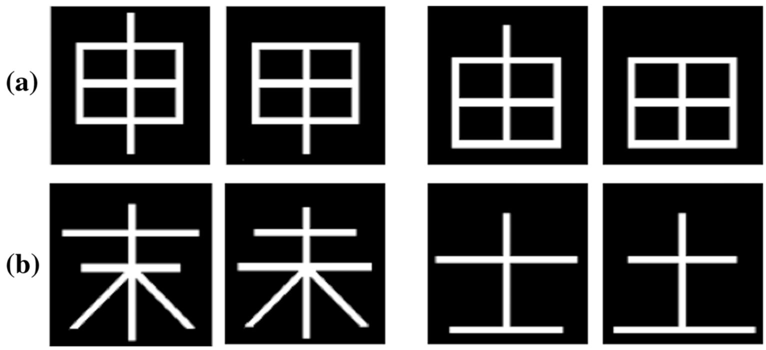

Fig. 1 Two types of line characters constructed as fundamental stimuli in CP experiments: **a** Absolute-Differentiation (AD) type, and **b** Relative-Differentiation (RD) type

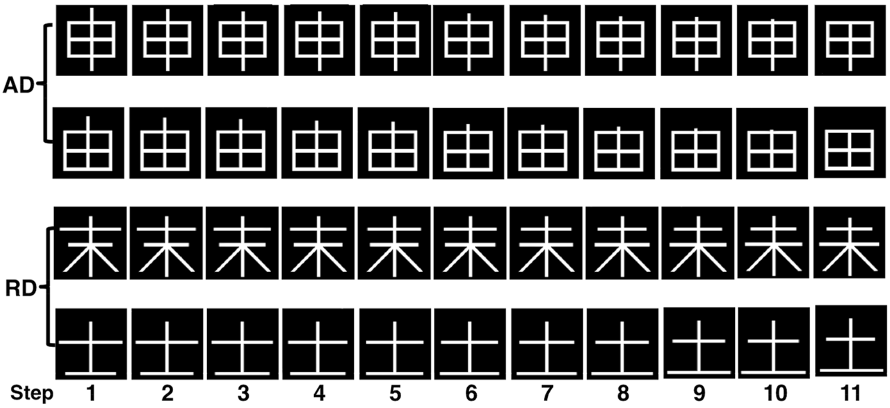

Fig. 2 Four groups of 11-step stimulus continuum

Experimental design

The experiment had a within-subject independent variable, stimulus *type* (AD vs. RD) and a between-subject independent variable, *group* (different long-term experiences in reading and using simplified and traditional Chinese characters (MLC vs. HKC)). The dependent variables were the identification scores and discrimination scores, which are described in the data analysis section.

Procedure

There were two tasks for each participant in the current experiments, the identification and discrimination tasks, with the discrimination task preceding the identification task for all participants. Each stimulus spanned 1.58° of visual angle vertically and 1.07° horizontally with an 80-cm viewing distance. The design and control of experiments were conducted with E-Prime v2.0 psychology software and presented on a 17-inch computer screen.

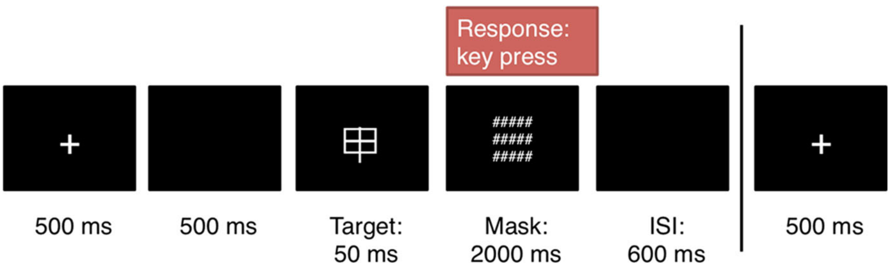

Fig. 3 Sequence of a trial in the identification task

Identification task

In the identification task as shown in Fig. 3, four sets of 11-step continua were arranged into four blocks. In each block, one of the four continua was presented, with the 11-step stimuli randomly ordered. In each block, the two endpoints of each continuum served as the representative targets, and participants were instructed to press corresponding keys to make identification decisions. In each trial, after a 500-ms central fixation and another 500-ms blank, a line-character stimulus chosen from the four sets of continua was presented on the computer screen for 50 ms. Next, a mask was shown for 2000 ms during which participants were instructed to press a corresponding key on the computer keyboard to judge what the character was as quickly and accurately as possible. The mask disappeared once participants pressed the key or ended automatically after 2000 ms, after which a 600-ms blank frame appeared as the inter stimulus interval (ISI hereafter). The 50-ms presentation time for the target stimuli and the use of a mask were constructed to correspond to the experimental setting of Peng et al. (2010a), which suggested that such settings made the stimulus presented at the threshold of visibility and perceived liminally by participants—"participants were aware that a stimulus had been presented but were unable to consciously identify the stimulus (Peng et al. 2010a, p. 420)". The 11 stimuli of each continuum were repeated ten times in the whole identification session, forming a total of 440 trials divided into 4 blocks. Participants completed 10 practice trials before the actual experimental trials. The order of continuum presentation was randomized and counter-balanced across participants in MLC and HKC groups.

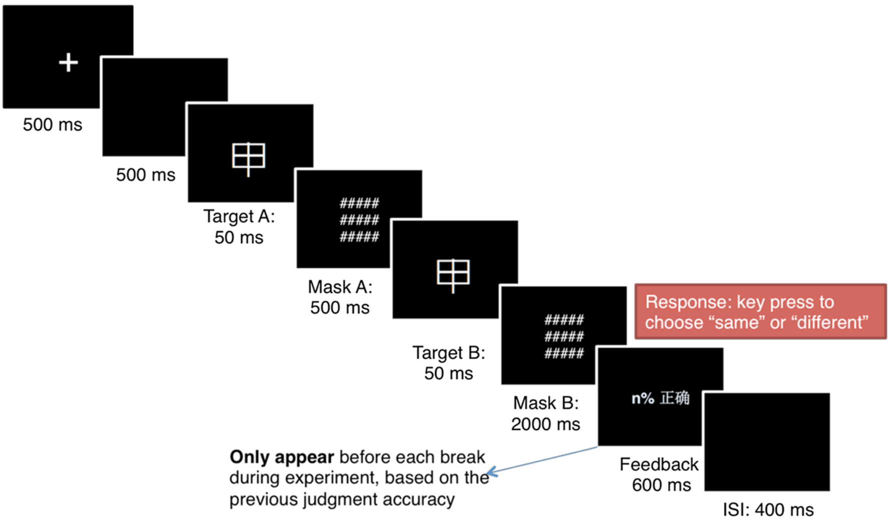

Fig. 4 Sequence of a trial in the discrimination task

Discrimination task

For the discrimination task, we employed the AX paradigm. As shown in Fig. 4, in each trial, after a 500-ms central fixation and another 500-ms blank, the first line-character stimulus chosen from the above four sets of continua was presented on the computer screen for 50 ms after which the first mask was shown for 500 ms. Then, the second line-character stimulus was shown for 50 ms, which was chosen from the same set of continua as the first stimulus but was 3 steps different or the same. After the second line-character stimulus, the second mask appeared for 2000 ms during which time participants were instructed to press a key on the computer keyboard to judge whether the previous two stimuli were the same or different as quickly and accurately as possible. The second mask disappeared once participants pressed the key or ended automatically after 2000 ms after which a 400-ms blank frame appeared as the ISI. The reason for choosing 50 ms as the presentation time for each target stimulus and the use of the mask were the same as the settings in the identification task. Moreover, to make participants concentrate on the task, feedbacks about reaction accuracy were provided during block breaks on the screen.

A total of 496 trials were presented randomly in the discrimination task. Of these pairs, 320 consisted of two different stimuli separated by 3 steps (our pilot study found that the 1-step and 2-step differences were too difficult for participants to discriminate; therefore a 3-step discrimination was adopted for the formal experiment) on the four line-character continua (different pairs) in either forward (1–4, 2–5, 3–6, 4–7, 5–8, 6–9, 7–10, 8–11) or reverse order (4–1, 5–2, 6–3, 7–4, 8–5, 9–6, 10–7, 11–8). There were 5 occurrences for each 3-step pair, divided into 2 blocks, with 3 occurrences in one block and 2 occurrences in the other. The other 176 pairs contained one of the eleven stimuli on each continuum paired with itself (same pairs). There were 4 occurrences of each same pair, equally divided into the 2 blocks. The order of presenting stimulus pairs was randomized, and the blocks were counter-balanced across participants from MLC and HKC groups. Before the formal experiment, each participant was required to do a practice task that shared the same paradigm with the formal test, and participants must obtain at least 70% accuracy within five trials of the practice sessions to enter the formal experiment.

Data analysis

To investigate the effects of group (HKC vs. MLC) and stimulus type (AD vs. RD) on identification and discrimination performance, we measured the following essential characteristics of CP for each participant: the sharpness of the category boundary and the position of the category boundary from identification scores, and the between-category discrimination sensitivity from the discrimination scores.

Identification scores

For each stimulus in this experiment, the identification score is defined as the percentage of different responses for which participants identified as the stimulus.

The method and formula described by Xu, Gandour, and Francis (2006) were adopted to analyze identification scores. Based on the binomial distribution of identification scores and the sigmoid shape of the identification response function, a logistic regression between the raw identification scores (P_1) and the repeated measure predictor, step number (x), were adopted to obtain the mean identification function for each subgroup of stimuli, as shown in Eq. (1):

$$\log_e\left(\frac{P_1}{1-P_1}\right) = b_0 + b_1 x \tag{1}$$

The regression coefficient b_1 was used to evaluate the slope of the fitted logistic curve and was an indication of *the sharpness of the categorical boundary*. b_0 is the coefficient of the constant. The mean *position of the categorical boundary* in each subgroup was derived from the step number (x_{cb}) corresponding to the 50% identification score, as shown in Eq. (2):

$$b_0 + b_1 x_{cb} = \log_e\left(\frac{0.5}{1-0.5}\right) = 0 \Rightarrow x_{cb} = -\left(\frac{b_0}{b_1}\right) \tag{2}$$

Discrimination scores

To obtain discrimination scores for each pair, calculations were made by using the formula described in Xu et al. (2006), as shown in formula (3). Each unit comprised all trials involving the four types of pairwise comparisons (AB, BA, AA, and BB), where AB and BA were “different pairs”, and AA and BB were “same pairs”. AA or BB trials were used in adjacent comparison units (e.g., the 4–4 pairs were used in both 1–4 and 4–7 units). The accuracy score P for each comparison unit was defined by the following formula (3):

$$P = P(``S''/S) \cdot P(S) + P(``D''/D) \cdot P(D) \tag{3}$$

in which P(“S”/S) denoted the percentage of “same” responses to all “same pairs” and P(“D”/D) denoted the percentage of “different” responses to all “different pairs”, i.e., the correct responses. P(S) and P(D) were the percentages of “same” and “different” pairs in each unit, respectively.

The obtained discrimination data for each subject were then examined by the *between-category discrimination sensitivity*, which was measured from the comparison unit corresponding to the position of the categorical boundary (x_{cb}) determined from the subgroup identification logistic functions. For example, for the AD-type stimuli, assume the position of categorical boundary x_{cb} was rounded to 8. Then, the between-category discrimination sensitivity was based on the discrimination comparison unit including the boundary position number. Since the current experiment recruited a 3-step discrimination, the 5–8, 6–9, 7–10 and 8–11 units all included the boundary position number 8, and thus the between-category discrimination sensitivity was measured by the average value of the above four comparison units.

Results

Raw identification and discrimination curves

The raw mean identification and discrimination curves are presented in Figs. 5 and 6, suggesting that MLC and HKC participants processed the two types of line-character stimuli in the CP paradigm differently. Further statistical analyses on raw identification and discrimination data provide supportive evidence showing the difference and are reported in the following sections.

Logistic identification functions

The estimated regression coefficients for the mean logistic response functions of two types of line-character stimuli by MLC and HKC participants are presented in Table 2.

Sharpness of category boundary

The sharpness of the category boundary was evaluated by the b_1 coefficient of the logistic function of identification scores (i.e., slope). A two-way, mixed, repeated-measures analysis of variance (ANOVA) was conducted to determine the impact of reader *group* (MLC and HKC) and stimulus *type* (AD and RD) on the sharpness of the category boundary, with *group* as the between-subject factor and *type* as the within-subject factor. All effects in this study were reported as significant at $p < 0.05$ and as marginally significant at $p < 0.1$.

A significant main effect of *group* [F (1, 39) = 5.47, p = 0.025] suggested that the MLC (Mean = 1.04, SE = 0.09) group had sharper boundaries for both AD and RD than the HKC group (Mean = 0.75, SE = 0.09). The main effect of *type* was marginally significant [F (1, 39) = 3.00, p = 0.091]. There was also a marginally significant interaction effect of *group* and *type* [F (1, 39) = 2.88, p = 0.098]. To clarify the difference between the MLC and HKC groups, we constructed several planned comparisons. Independent-samples t-tests revealed that only for AD-type

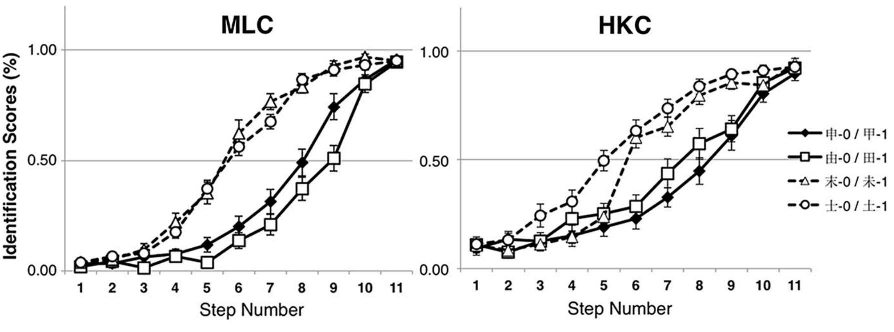

Fig. 5 Raw identification curves of MLC and HKC participants. Error bars represent the standard error of means (SEM hereafter)

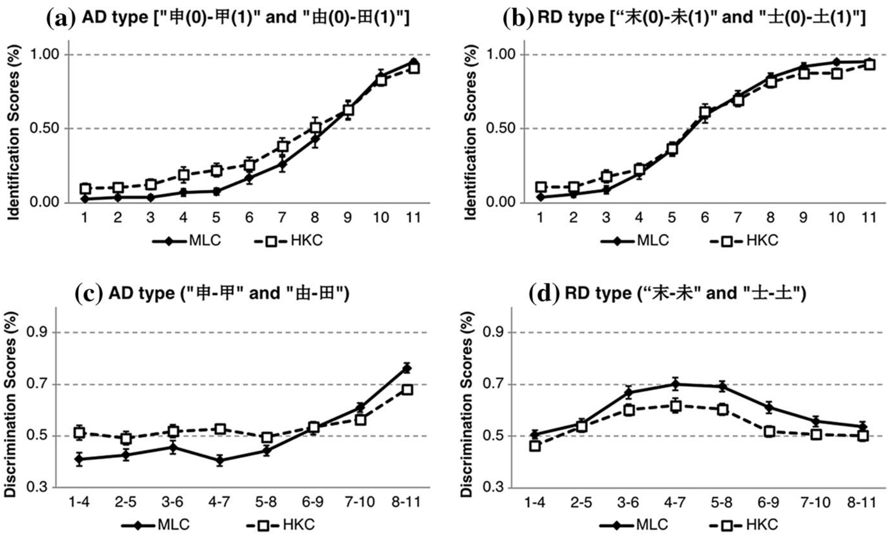

Fig. 6 Identification curves of AD-type (**a**) and RD-type (**b**) stimuli, and discrimination curves of AD-type (**c**) and RD-type (**d**) stimuli by MLC and HKC participants. Error bars represent SEM

Table 2 Estimated logistic regression coefficients (b_0, b_1) and the derived categorical boundary (x_{cb}) for each line-character group in MLC and HKC participants

Subgroup	b_0		b_1		$x_{cb} = -b_0/b_1$	
	MLC	HKC	MLC	HKC	MLC	HKC
AD (申-甲 and 由-田)	− 9.5459	− 5.5335	1.1930	0.7555	8.0015	7.3241
RD (末-未 and 土-土)	− 5.0914	− 4.2774	0.8844	0.7526	5.7569	5.6840

stimuli, the MLC group (Mean = 1.19, SE = 0.14) had a significantly sharper category boundary than the HKC group (Mean = 0.76, SE = 0.14), t (39) = 2.24, $p = 0.016$. For RD-type stimuli, the MLC group (Mean = 0.88, SE = 0.06) also had a sharper boundary than the HKC group (Mean = 0.75, SE = 0.06), but the difference was only marginally significant, t (39) = 1.51, $p = 0.070$. As presented in Fig. 7, those results suggest that MLC and HKC participants showed larger differences in processing AD-type stimuli than in processing RD-type stimuli.

Position of category boundary

Similar ANOVA on the position of the category boundary yielded only a significant main effect of stimulus *type*, with AD-type (Mean = 8, SE = 0.23) showing a larger boundary position number than RD-type (Mean = 6, SE = 0.11), F (1, 39) = 53.53, $p < 0.001$. Further independent-samples t-tests showed that for AD-type stimuli, the group effect was marginally significant, with MLC (Mean = 8, SE = 0.24)

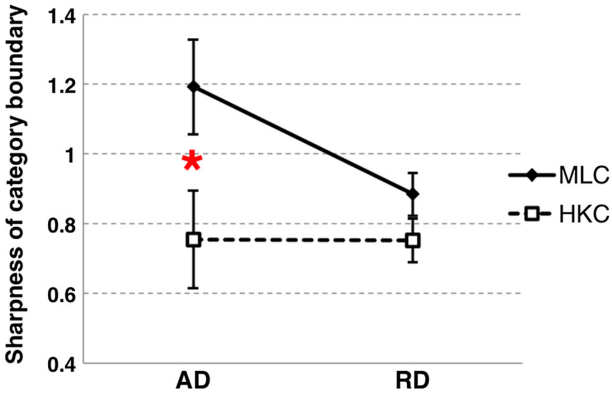

Fig. 7 Means of slope values (b_1) from the logistic identification functions of AD-type and RD-type stimuli for MLC and HKC participants. Error bars represent SEM. "*" indicates significant difference ($p < 0.05$)

larger than HKC (Mean = 7, SE = 0.41) group: t (39) = 1.45, $p = 0.077$, indicating that the mean boundary positions for MLC participants for identifying the AD-type stimuli shifted more toward the "甲/田" end than those for HKC participants. By contrast, for RD-type, the group effect was not significant, t (39) = 0.328, $p = 0.372$ (MLC: Mean = 6, SE = 0.16; HKC: Mean = 6, SE = 0.16), suggesting that MLC and HKC participants had similar category boundary positions in identifying RD-type stimuli. Generally, in terms of the position of the category boundary, MLC and HKC participants were more different in their processing of AD-type stimuli, as shown in Fig. 8.

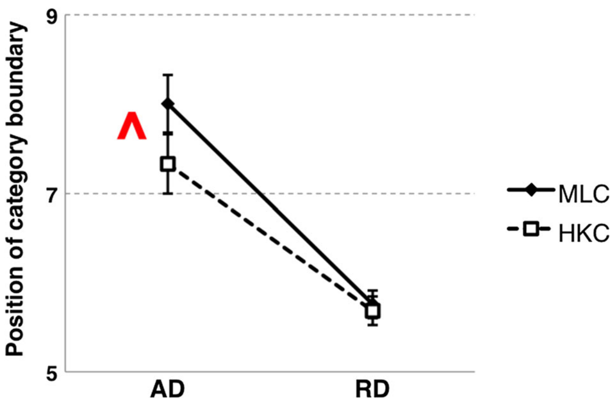

Fig. 8 Means of identification boundary positions of AD-type and RD-type stimuli for MLC and HKC participants. Error bars represent SEM. "^" indicates marginally significant difference ($p < 0.1$)

Between-category discrimination

A similar analysis showed significant *group* [F (1, 39) = 22.35, $p < 0.001$] and *type* [F (1, 39) = 12.30, $p = 0.001$] main effects in between-category discrimination sensitivity. The *group* × *type* interaction effect was not significant, indicating that MLC showed higher discrimination sensitivity than HKC for both AD-type (MLC: Mean = 0.61, SE = 0.02; HKC: Mean = 0.51, SE = 0.02) and RD-type stimuli (MLC: Mean = 0.63, SE = 0.01; HKC: Mean = 0.57, SE = 0.01), as presented in Fig. 9. This difference was also revealed by two independent-samples *t*-tests: for AD-type, t (39) = 4.24, $p < 0.001$; for RD-type, t (39) = 3.26, $p = 0.001$.

Discussion

Altogether, the results reported above confirm our prediction that MLC and HKC participants show different degrees of CP effects in identification and discrimination tasks when perceiving Chinese characters. Such results suggest that MLC and HKC participants may use different strategies to process AD-type and RD-type stimuli constructed based on real characters, which share the same configurations in traditional and simplified Chinese scripts but differ in their topological properties.

The above results also suggested that both types of stimuli continua were perceived categorically or at least quasi-categorically. The concept "quasi-categorical" was proposed to describe a gradient of categoricity in speech perception (Hallé et al., 2004). Similarly, in the current CP experiment on character perception, we also adopted a liberal view of CP. That is, CP effects occur when (1) a set of stimuli ranging along a physical continuum is given one label on one side of a category "boundary" and another label on the other side, and (2) participants can discriminate smaller physical differences between pairs of stimuli that straddle the boundary than between pairs that are within one category or the other. By contrast, a

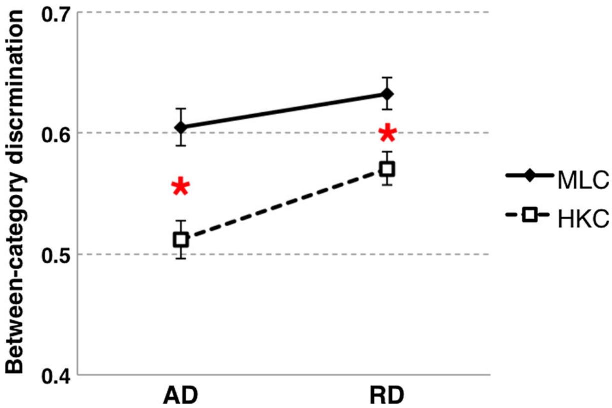

Fig. 9 Between-category discrimination sensitivity in percentage correct of AD-type and RD-type stimuli for MLC and HKC participants. Error bars represent SEM. "*" indicates significant difference ($p < 0.05$)

stringent definition of CP requires an optimal fit between the observed discrimination performance and the performance predicted from identification, but in many cases, such an ideal fit is not obtained. For the current experiment, the most direct evidence for CP effects on perceiving the two types of stimuli came from the observation that discrimination peaks corresponded mostly to the stimulus number where boundary positions were located. Specifically, for AD-type stimuli, the discrimination peaks for the MLC and HKC groups both appeared at the 8–11 pair (see Fig. 6c), which corresponded to boundary position 8 for MLC's identification curve and position 7 for HKC's identification curve (see Table 2). Additional evidence for CP effects was that MLC and HKC participants had higher discrimination scores in stimuli straddling the boundary for both the AD-type and RD-type stimuli (see Fig. 6c, d).

Moreover, the above observations revealed that the discrimination peak in AD-type and RD-type stimuli presented different patterns. For RD-type stimuli, no sharp peak appeared as in the case of stop-consonant continua, but only shallow broad peaks or a plateau emerged. Such a result indicates that these stimuli were perceived categorically by both MLC and HKC readers but were not as categorical as the case of stop consonants (Liberman et al., 1957) and corresponded more to the CP pattern of vowels (Fry et al., 1962; Pisoni, 1975) and level tones (Abramson, 1979; Francis et al., 2003). By contrast, the discrimination peak was much more obvious and sharper in AD-type stimuli, which corresponded to the case of stop consonants. For the similarity between the CP pattern of visual RD-type stimuli and auditory vowels and level tones, a possible reason is that both of them contain extensive information, which requires more viewing space (no topological transformation) or listening time to become fully available for perception. By contrast, the crucial information for discrimination of AD-type stimuli appears to be available in a much narrower viewing space and induces a sharp topological transformation, which is comparable to the rapid consonant–vowel transitions and transient-release bursts in stop-consonant perception, thus making the discrimination peak much sharper for AD-type stimuli. Overall, given that AD-type and RD-type stimuli differ in topological properties, the different processing results shown in CP tasks indicate that different topological properties may play different roles in perceiving the two types of stimuli for MLC and HKC participants.

Can the topological properties embedded in these two types of stimuli be generalized to other characters across both Chinese writing systems? To answer this question, we examined characters with similar configurations ("形近字") in a dictionary, which systematically collected simplified Chinese characters sharing similar configurations (Wang, 1995). Intriguingly, the number of characters that share identical topological properties and use relative change to differentiate between them is very limited. Except for the ones used in the current experiment ("士" and "土", "末" and "未") and the ones constructed by using them as a component (i.e., "妹" and "妺", "沫" and "沬", "昧" and "眛"), a very limited number of character pairs can be defined with the RD standard, whereas the number of characters that have different topological properties but share similar configurations is large, as illustrated in following Table 3. Moreover, there are other types of characters that are also differentiated by altering topological properties, such as

Table 3 Illustration of simplified characters with similar configurations that belong to AD-type and RD-type stimuli

AD	RD
申, 甲; 由, 田; 呻, 呷	末, 未
八, 人	士, 土
胃, 胄	日, 曰
工, 土	人, 入; 仚, 氽
天, 夫	妹, 妺; 沫, 沬; 昧, 眛/眜
己/已, 巳	
午, 牛	
佘, 余	
苦, 若	
目, 且	

by adding a stroke (e.g., "未, /wei4/, not yet" and "朱, /zhu1/, scarlet or a surname", "大, /da4/, big" and "太, /tai4/, extremely", etc.), altering radicals ("埃, /ai1/, dust" and "挨, /ai1/, get close to", "澳, /ao4/, bay" and "懊, /ao4/, regretful", etc.), or manipulating in other ways. Although these characters are not differentiated through one dimension of topological properties in their configurations, as in "甲-申" and "田-由", large number of characters with similar configurations are differentiated by altering topological properties. Obviously, topological transformation is much more productive for constructing characters, as well as for differentiating characters with similar configurations. Such arguments are also supported by evidence from the history of character development in which some characters previously were differentiated using relative change (identical topological properties) on some specific strokes but were changed later using different topological properties, as also discussed by Liu (1993). For example, "上 (/shang4/, up)" and "下 (/xia4/, down)" were previously written as "" and "" in oracle bone inscriptions (OBI) or as "" and "" in bronze inscriptions, which had identical topological properties and were differentiated by the relative length and position of the two strokes. Another similar example was "王 (/wang2/, the king or a surname)" and "玉 (/yu4/, jade)", which were written as "王" and "王" in small seal script ("小篆" in Chinese) with identical topological properties. It is therefore possible that differentiating characters by changing their topological properties actually makes use of the features of the human visual system, which is very sensitive to the global topological properties of an object. Based on our current knowledge and searching, a comparable dictionary on traditional characters has not been located. However, since the two Chinese writing systems share structures, the above observation from simplified characters should also be generalizable to traditional characters to a large extent.

Apart from the difference in processing AD-type and RD-type stimuli, another notable phenomenon was that MLC and HKC participants showed major differences in perceiving AD-type stimuli rather than RD-type stimuli. This difference was mainly indexed by the sharper category boundary and larger boundary position number in perceiving AD-type stimuli in the MLC group than in the HKC group. The MLC group also had higher between-boundary discrimination sensitivity than the HKC group for both AD-type and RD-type stimuli. Given that the number of characters that differ from each other in several dimensions of topological properties is very large, and simplified characters should also differ from traditional characters in terms of topological properties and other levels of visual complexity (such as stroke, component and structural differences), it seems natural to observe the major processing differences in AD-type stimuli rather than RD-type stimuli by MLC and HKC readers. Moreover, in our experimental design, the AD-type and RD-type stimuli were differentiated in their topological properties, i.e., the topological pattern changes along the AD-type continuum (at least two topological properties, closure and connectivity, change from "申" to "甲" and from "由" to "田") but not in the RD-type continuum. Chen (2005) proposed a theory regarding the topological approach to perceptual organization and provided empirical evidence to suggest that a primitive and general function of the visual system may be the perception of global topological properties of visual objects, i.e., geometrical invariance under stretching. The major difference between MLC and HKC readers' performance in AD-type stimuli indicates that they might also show differences in topological perception. Since topological properties reflect the global information of an object, the current results seem to further suggest that MLC and HKC readers might have different levels of holistic processing (i.e., obligatory attention to all parts of an object). In addition, Chen, Zhang, and Srinivasan (2003) reported that honeybees possess the ability for topological perception, suggesting that topological perception is an old and fundamental property of vision for both humans and animals. However, the above results seemed to suggest that topological perception could be shaped by later visual experiences, and here, we presume different writing-system experiences. Nonetheless, the observations and questions raised in the above discussion cannot be totally clarified in the current experiment, but merit further studies to examine, with better control of the possible cofounding factors (such as spoken languages, exposure to other languages, teaching strategies, more detailed investigations on reading experiences, etc.).

In conclusion, by using a CP paradigm, we constructed minimal grapheme pairs of Chinese characters as phoneme comparisons and presented the stimuli to adult MLC and HKC readers for a 50-ms duration that corresponded to the liminal perception threshold. Based on this design, we showed positive evidence of CP effects on character perception by the two groups of Chinese readers. We also extended previous results regarding the comparison of visual skills of simplified and traditional Chinese script readers and provided supportive evidence for the hypothesis that simplified Chinese script readers have higher visual discrimination rates than do traditional Chinese script readers in character perception.

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