Blue–green color categorization in Mandarin–English speakers

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Observers are faster to detect a target among a set of distracters if the targets and distracters come from different color categories. This cross-boundary advantage seems to be limited to the right visual field, which is consistent with the dominance of the left hemisphere for language processing [Gilbert *et al.*, Proc. Natl. Acad. Sci. USA **103**, 489 (2006)]. Here we study whether a similar visual field advantage is found in the color identification task in speakers of Mandarin, a language that uses a logographic system. Forty late Mandarin–English bilinguals performed a blue–green color categorization task, in a blocked design, in their first language (L1: Mandarin) or second language (L2: English). Eleven color singletons ranging from blue to green were presented for 160 ms, randomly in the left visual field (LVF) or right visual field (RVF). Color boundary and reaction times (RTs) at the color boundary were estimated in L1 and L2, for both visual fields. We found that the color boundary did not differ between the languages; RTs at the color boundary, however, were on average more than 100 ms shorter in the English compared to the Mandarin sessions, but only when the stimuli were presented in the RVF. The finding may be explained by the script nature of the two languages: Mandarin logographic characters are analyzed visuospatially in the right hemisphere, which conceivably facilitates identification of color presented to the LVF.

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1. INTRODUCTION

A classic problem in color perception is the relationship between language and perception. Color names divide the physically continuous wavelength spectrum into discrete categories and the question is whether the categorization of colors based on color names has an effect on the speed and accuracy of color processing. In color naming tasks, observers are usually slower in naming a color that is close to the color boundary in comparison to a color close to the center of a color category [1]. This is akin to categorical speech perception where listeners partition voice-onset times into discrete phonetic categories, and identification is slow for stimuli that fall near boundaries between categories and fast for stimuli that fall away from such boundaries [2].

Recently, a visual search task was designed in which observers were asked to detect a color target among a set of similar-colored distracters (for a review see [3]). Target and distracters could either be in the same color category (e.g., both blue or both green) or in different categories (e.g., target is blue, distracters are green, or vice versa). Observers were usually faster and more accurate in detecting the target when the target and distracters belong to different color categories, supporting the idea of "categorical perception" in color processing. Critically, search reaction times (RTs) were found to be significantly shorter when stimuli were displayed in the right visual field (RVF) [4]. The result was interpreted as indicating temporal advantage due to color processing in the "language" left hemisphere.

Further support for the effect of language on perceptual color organization comes from Athanasopoulos and colleagues' research of Greek–English [5,6] and Japanese–English [7] bilinguals. It was demonstrated that high proficiency in English (L2), prolonged immersion into an L2 speaking environment, and amount of L2 use are factors influencing conceptual partitioning of color space in bilinguals. These authors found in Greek–English speakers a shift of the focal color of the Greek *ble*, "dark blue," to that of the English *blue*; similarly, "long-stay" Japanese–English bilinguals revealed decreased sensitivity to the distinction between the two Japanese terms for blue, *ao*, "dark blue," and *mizuiro*, "light blue." These findings provide evidence that the color perception structure of bilingual individuals is flexible, dynamic, and contingent on the language in use.

Unlike the above-named bilingual studies assessing focal colors, in the present study we questioned whether color category boundary varies in the two spoken languages. In addition, we probed temporal advantage for color stimuli presented in the RVF. These questions were addressed in a blue–green categorization task in bilingual Mandarin–English speakers while assessing their category boundary, by means of response frequencies and response times at the boundary, in Mandarin and in English, for the RVF and the left visual field (LVF).

2. METHODS

A. Equipment

Stimuli were displayed on a CRT monitor (21 in. Sony GDM-F520) that was controlled by a DELL PC with a ViSaGe stimulus generator (Cambridge Research Systems, Ltd.). The lookup tables were linearized using the ColourCal calibration device (Cambridge Research Systems, Ltd.) which interfaces with the stimulus generator. Calibration was checked with a PR650 telespectroradiometer (PhotoResearch). The CIE coordinates (x, y, luminance) of the CRT phosphors at peak output were as follows: red = 0.627, 0.342, 28.12; green = 0.287, 0.608, 80.96; and blue = 0.151, 0.074, 14.16. Since there was some initial monitor drift, the monitor was switched on at least 1 h before the start of the experiment. The responses of the observers were registered using a button box (CT6, Cambridge Research Systems, Ltd.). Stimuli were generated using the CRS MATLAB toolbox and MATLAB 7.6.

B. Subjects

Forty bilingual Mandarin–English speakers participated in the experiments (nine males; average age, 24.2 years). All subjects were native Mandarin (L1) speakers and late English (L2) bilinguals, i.e., they learned English after 6 years of age. Subjects completed the Nation Vocabulary Test [8], which allowed us to assess their proficiency in English, their L2. The average score in the Nation Vocabulary Test was 62.5 (out of a maximum score of 90), reflecting an intermediate proficiency; only three bilinguals reached a score of lower than 50. A group of native English monolinguals ($n = 27$; five males and 22 females; average age, 20 years) served as controls. All participants were naïve as to the purpose of the experiments. Subjects were recruited via posters and the university e-mail announcement system. The control group was recruited via the Experimental Participation Programme, which requires each psychology undergraduate student to participate in experiments. Informed consent was obtained from all subjects prior to the experiment. All subjects had normal or corrected-to-normal visual acuity. Prior to the main experiment, observers were screened with the Trivector test of the Cambridge Color Test [9]. Only observers whose color discrimination fell within the normal range took part in the main experiment; normal range was defined as thresholds lower than 100×10^{-4} u' v' units for the protan and deutan vectors and lower than 150×10^{-4} u' v' units for the tritan vector. The experiments were approved by the ethics committee of the School of Psychology, University of Liverpool.

C. Stimuli and Procedure

On each trial, a single 2° patch was presented for 160 ms 1° away from the central fixation target either in the LVF or the RVF of the observer [Fig. 1(a)]. The location of the visual field (VF) was chosen randomly, but each color was presented equally frequent in each VF. The "Mandarin" and "English" sessions were run in blocks. After stimulus presentation, the color names ("blue" or "green," either in English or in Mandarin) were presented in the top and bottom of the screen (*randomly chosen*) until the observer indicated by a button press the color name most appropriate for the presented patch [Fig. 1(a)]. 1000 ms (with a random jitter of ±200 ms) after the response was recorded, the next trial started.'

1. Chromaticities

The 11 color patches spanned a range of colors [Fig. 1(b)] between the unique blue (at 240°; CIELuv) to unique green (140°), with intermediate hues separated by 10° steps (equivalent to 6 ΔE). All colors had the same saturation and lightness levels (L = 60, luminance = 36.4 cd/m^2). The chosen endpoints of the hue range (unique blue and unique green) were based on a large set of previously collected data [10,11]. The background was kept constant at midlevel gray (CIE $x = 0.295$, $y = 0.297$, luminance = 17.9 cd/m^2).

2. Procedure

Each observer came to the laboratory on two different days and, on each day, two sessions were run, either two "Mandarin" sessions or two "English" sessions. The order of these sessions was counterbalanced: 20 observers ran first the two Mandarin sessions and on a subsequent day the English sessions; for the other 20 observers, it was vice versa. Participants were immersed in the tested language: the experimenter welcomed them in that language; all instructions were given in the language to be tested, as well. Each of the four sessions lasted about 10–15 min.

Each session started with a short adaptation period (3 min) to ensure steady adaptation to the gray background. The observer started the experiment by pressing a button. In each

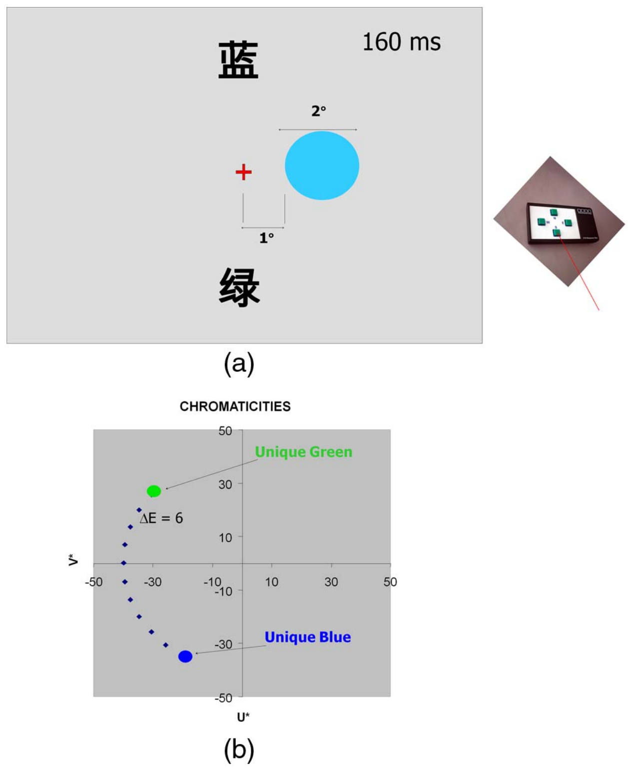


Fig. 1. (Color online) (a) Stimuli. On each trial, a single 2° patch was presented for 160 ms 1° away from the central fixation target either in the LVF or the RVF of the observer, while the observer fixated the central target. After stimulus presentation, the color names ("BLUE" or "GREEN," either in English or in Mandarin) were presented in the top or bottom half of the screen. Both names were presented equally often in the bottom and top halves; on each trial, the location was chosen randomly. (b) The 11 color patches spanned a range of colors between the unique blue (at 240°; CIELuv) and unique green (140°), with intermediate hues separated by 10° steps (equivalent to 6 ΔE).

session, each of the 11 colors was presented 20 times on the left and 20 times on the right side, in a random order. On each trial, the observer made a binary decision by indicating whether the patch was categorized blue or green. The response and the RT were recorded after each trial.

3. RESULTS

Our main aim was to investigate whether bilingual individuals possess differently structured perceptual color spaces contingent on the language in use [5–7]. A second aim was to test whether the influence of language on color categorization is specific to a particular hemisphere, as suggested by controversial previous findings [3,4, but see also 12,13]. To that end we derived two response measures: the blue–green color boundary and the RTs at the color boundary, for both VFs and for both languages, L1 and L2. Our main result is that the color boundary is independent of the VF or the language, whereas the speed of categorization at the color boundary is greater for the stimuli presented in the LVF but only when bilingual observers categorized the colors in Mandarin.

A. Blue–Green Boundary

To estimate the blue–green boundary, we derive the cross-over point of the "blue" and "green" frequency curves [Fig. 2(a)]; the hue at which observers are equally likely to categorize the color as "green" or "blue" is defined as the blue–green boundary [1] [indicated by the red arrow in Fig. 2(a)]. Instead of using the empirical frequency distributions, we fit a Weibull function to the data of each individual observer and calculate the midpoint. Figure 2(a) shows an example distribution (Observer #5, Left Visual Field, MANDARIN); green symbols denote the frequency of responding "green" as a function of the hue angle; data are replotted for clarity in terms of frequency of "blue" categorization, shown in blue symbols. Solid curves are fitted Weibull distributions, commonly used to model psychometric functions (e.g., [14]). The Weibull functions were fitted using the MATLAB 7.12 (MathWorks) optimization routines; the location and the slope were free parameters; lower and upper asymptotes are fixed. The data for each observer ($N = 40$) were fitted individually; for each observer, the blue–green boundary was derived for each of the four conditions: MANDARIN or ENGLISH, LVF or RVF.

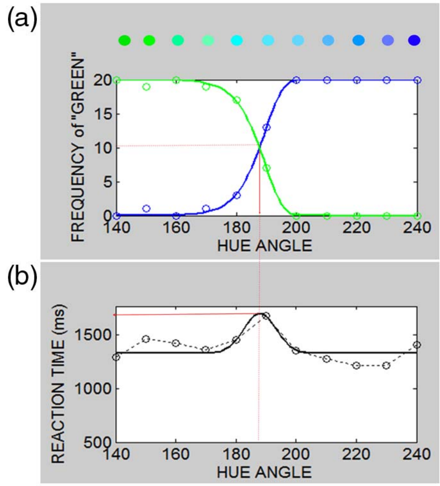


Fig. 2. (Color online) (a) The blue–green color boundary was obtained by fitting a Weibull function (solid curve) to the data of each individual observer. Open green symbols denote the frequency of responding with "GREEN" as a function of hue angle; data are replotted for clarity in terms of frequency of saying "BLUE" and are shown in blue open symbols. The cross over of the fitted BLUE and GREEN response curves is defined as the blue–green boundary. (b) The blue–green boundary is then used to estimate the RT at the color boundary. To summarize the RT distribution, we fit a peak function, namely, the sum of a Gaussian and a constant where the locations of the peak is fixed at the color boundary. The fitted amplitude at the blue–green boundary is used as an estimate for the RT.

Histograms of the blue–green boundaries are shown Fig. 3 for MANDARIN/LVF (upper left), MANDARIN/RVF (upper right), ENGLISH/LVF (lower left), and ENGLISH/RVF (lower right). The solid vertical line indicates the mean blue–green boundary (183.8° in Luv space) and the dotted vertical line the median. χ^2 goodness of fit tests ("chi2gof," MATLAB statistics toolbox) revealed that all four distributions are normally distributed (MANDARIN/LVF: $\chi^2 = 4.41$, $\mathrm{df} = 3$, $p = 0.22$; MANDARIN/RVF: $\chi^2 = 3.57$, $\mathrm{df} = 3$, $p = 0.31$; ENGLISH/LVF: $\chi^2 = 4.41$, $\mathrm{df} = 3$, $p = 0.22$; ENGLISH/RVF $\chi^2 = 1.03$, $\mathrm{df} = 2$, $p = 0.60$).

Figure 4(a) shows the average blue–green boundary for the LEFT and the RIGHT VFs, for both MANDARIN (red star) and ENGLISH (blue circle). Error bars denote 2 standard deviations. The average location of the blue–green boundary is

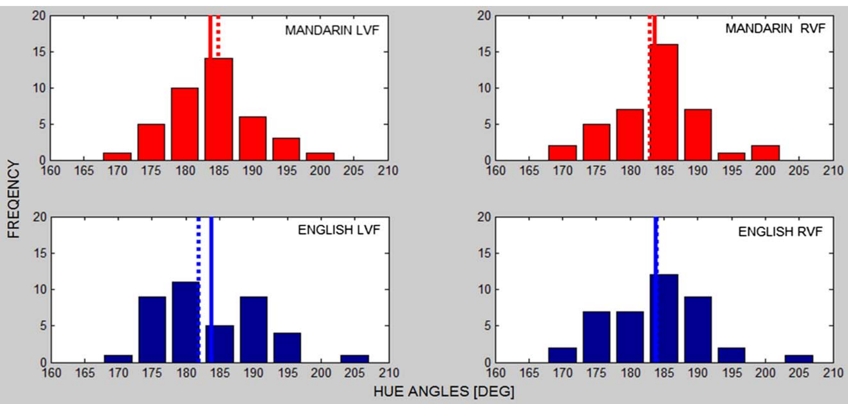
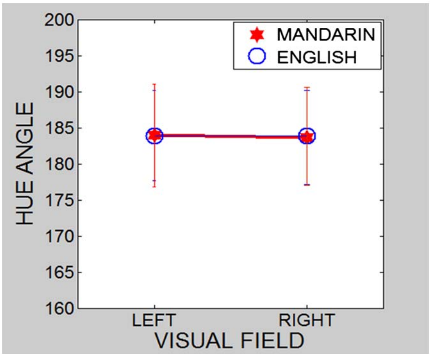
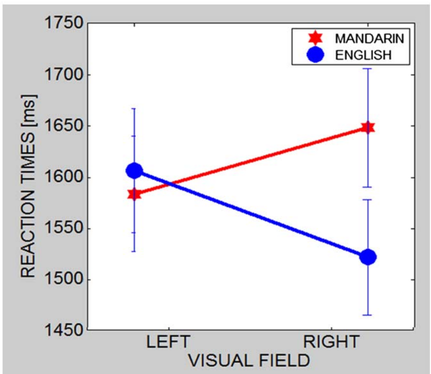


Fig. 3. (Color online) Histograms of the blue–green boundaries are shown for MANDARIN/LVF (upper left panel), MANDARIN/RVF (upper right), ENGLISH/LVF (lower left), and ENGLISH/RVF (lower right). The solid vertical line indicates the mean blue–green boundary (184° in Luv space) and the dotted vertical line the median. χ^2 gooodness of fit tests revealed that all four distributions are normally distributed.



(a)



(b)

Fig. 4. (Color online) (a) Average blue–green boundaries for LEFT and RIGHT VFs, for both MANDARIN (red star) and ENGLISH (blue circle) are plotted. Error bars denote 2 standard deviations. The average location of the blue–green boundary is at 184° (range: 169°–204°). (b) Mean RTs at the blue–green boundary are shown for both languages and for both VFs. Error bars denote 2 standard errors of the mean.

at 183.8° (range: 169°–204°); there are no differences in the location of the blue–green boundary between the LVF and RVF, nor do the boundaries differ when the native Mandarin speakers were tested in ENGLISH compared to MANDARIN.

In addition to testing for differences in the location of the color boundary, we also analyzed the steepness of the psychometric functions [Fig. 2(a)] for all four conditions (LVF/RVF, ENGLISH/MANDARIN). In the experimental group (late Mandarin–English bilinguals), the slopes of the psychometric functions are the same for all four conditions; there is no effect of VF and language, and no significant interaction between language and VF. Hence we have no evidence that, in bilinguals, color boundaries in the second language are broader (or less stable) than in the first language.

B. Reaction Times at the Blue–Green Boundary

The blue–green boundary obtained from the frequency curves [Fig. 2(a) are then used to estimate the RT at the color boundary [Fig. 2(b)]. To summarize the RT distribution, we fitted a peak function, namely, the sum of a Gaussian function and a constant, with the location of the peak fixed at the color boundary. The fitted value at the blue–green boundary is used as an estimate for the RT.

RT distributions are shown in Fig. 5 for MANDARIN/LVF (upper left graph), MANDARIN/RVF (upper right), ENGLISH/LVF (lower left), and ENGLISH/RVF (lower right). The solid vertical line indicates the arithmetic mean of the blue–green boundaries and the dotted vertical line the median. χ^2 goodness of fit tests did not reveal any significant violation of the normal distribution assumption (MANDARIN/LVF: $\chi^2 = 0.44$, df $= 3$, $p = 0.936$; MANDARIN/RVF: $\chi^2 = 5.24$, df $= 3$, $p = 0.07$; ENGLISH/LVF: $\chi^2 = 2.24$, df $= 2$, $p = 0.32$; ENGLISH/RVF $\chi^2 = 3.84$, df $= 3$, $p = 0.27$).

Mean RTs at the blue–green boundary are shown in Fig. 4(b), for both languages and for both VFs (MANDARIN/LVF: mean $=$ 1583 ms, standard error of the mean (SEM) $=$ 56 ms; MANDARIN/RVF: mean $=$ 1648 ms, SEM $=$ 57 ms; ENGLISH/LVF: mean $=$ 1606 ms, SEM $=$ 60 ms; ENGLISH/RVF: mean $=$ 1522 ms, SEM $=$ 56 ms). To test whether there is hemispheric specialization in the speed of blue–green categorization, we performed a two-way ANOVA with "language" and "visual field" as factors. We found no significant main effects of language or VF [language: $F(1,39) = 1.22$, $p = 0.27$; VF: $F(1,39) = 1.22, p = 0.64$] but a significant interaction between language and VF [$F(1,39) = 10.79, p = 0.002$]. From the *post hoc* comparisons, only one test reached statistical significance ($p < 0.05$, corrected for multiple comparisons): when the stimuli were presented in the RVF, RTs in the Mandarin sessions were longer than those in the English sessions. In a separate analysis, we tested for three-way

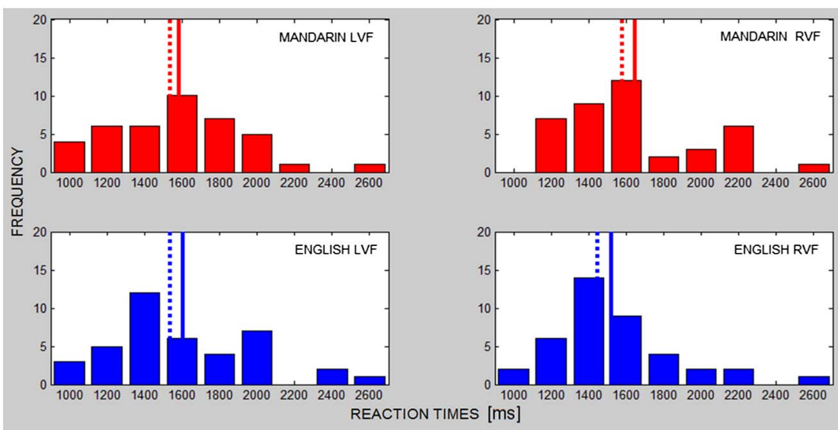


Fig. 5. (Color online) RT distributions are shown for MANDARIN/LVF (upper left graph), MANDARIN/RVF (upper right), ENGLISH/LVF (lower left), and ENGLISH/RVF (lower right). The solid vertical line indicates the arithmetic mean of the blue–green boundaries, and the dotted vertical line the median. χ^2 goodness of fit tests did not reveal any significant violation of the normal distribution assumption.

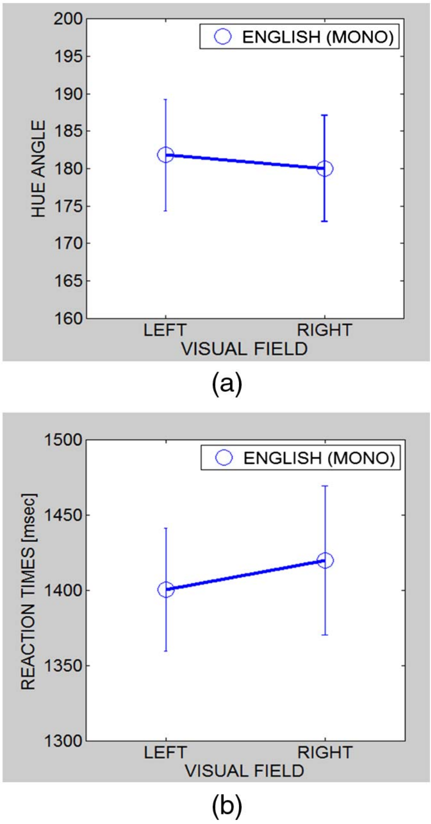


Fig. 6. (Color online) Data for control group (English monolinguals). (a) Average blue–green boundaries for the LEFT and the RIGHT VFs. Error bars denote 2 standard deviations. (b) Mean RTs at the blue–green boundary are shown for both VFs.

interactions (Language ∗ Visual Field ∗ Subjects); we found no significant interactions among language (English or Mandarin), VF (LVF or RVF), and subjects ($F = 0.41$, $p = 0.9985$).

We also tested how RTs in the blue–green categorization task (English session only) related to language proficiency in L2 (English) using a covariance analysis (aoctool, MATLAB statistics toolbox). RTs are negatively correlated with the language proficiency; that is, the more proficient the observer is in L2, the shorter the RTs at the color boundary; the relationship between RTs and language proficiency is the same for both VFs, however.

For the English monolingual control group, the average blue–green boundary in the LVF [boundary at 182°, standard deviation (SD) = 7; Fig. 6(a)] is similar to that in the RVF (boundary at 180°, SD = 7). Distributions with means (solid line) and medians (dashed lines) are shown in Fig. 7(a). RTs at the boundary did not differ significantly between the RVF [1406 ms, SD = 213 ms; Fig. 6(b)] and the LVF (mean = 1419 ms, SD = 257). Distributions are shown in Fig. 7(b), with the mean and median indicated by the solid and dashed lines, respectively.

4. DISCUSSION

Our first main result is that the location of the blue–green color boundary is independent of visual field and language in both the bilingual Mandarin–English and the monolingual English control group. This finding corroborates previous results, which reported no effect of hemifield on the blue–green boundary [1,15,16]. Our estimate of the location of the blue–green boundary (hue angle in CIELuv space = 184°, dominant wavelength = 492 nm) is in agreement with Bornstein and Monroe's [1] blue–green boundary at 491 nm, employing monochromatic lights. We also corroborate previous results by showing that RTs are slower at the color boundary compared to those to the colors close to the foci of the blue or green category [1]. These differences in processing speed between colors close to the foci as opposed to colors at the category boundaries are consistent with and complementary to visual search results for colors within versus across category boundaries [3,4,12,13].

Our more surprising result is that there was an interaction between language and VF in the speed of blue–green categorization: when the stimuli were presented in the RVF, RTs at the category boundary were longer in the Mandarin sessions than those in the English sessions for the late-bilingual speakers [Fig. 4(b)]. No hemispheric processing differences were found for the monolingual English speakers. A possible explanation for longer RTs for Mandarin (compared to English) in the RVF for the bilinguals is the right-hemisphere lateralization for written Chinese characters. A left-field advantage has been demonstrated for reading of Chinese characters

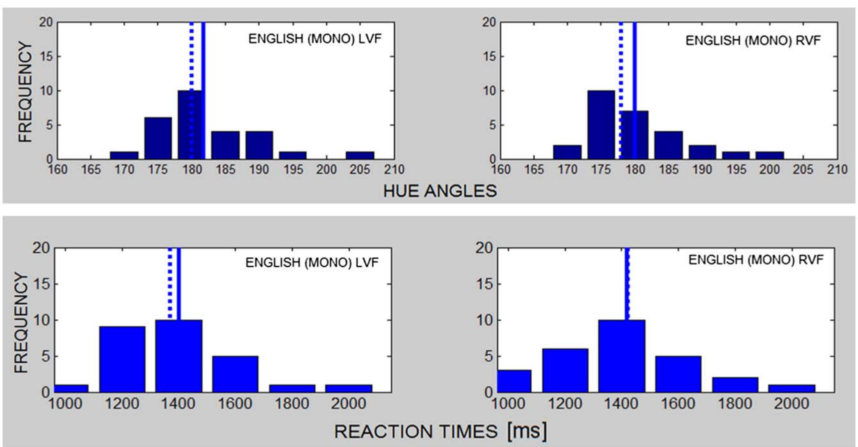


Fig. 7. (Color online) Distributions for monolingual English control group. (a). Histograms of the blue–green boundaries. The solid vertical line indicates the mean blue–green boundary and the dotted vertical line the median. (a) RT distributions for the monolingual English control group. The solid vertical line indicates the arithmetic mean of the blue–green boundaries, and the dotted vertical line the median.

[17,18], a logographic writing system, as opposed to the English (phonological) system. Recent functional imaging evidence has shown more activity in right-hemisphere cortical regions (i.e., Broadman areas 47/45, 7, 40/39) when participants were involved in reading Chinese relative to reading English [19]. We speculate that the hemispheric effect demonstrated in our experiment is closely tied in with the particular task, which forced observers to *read* the characters. It would be interesting to see whether a similar hemispheric effect in blue–green categorization can be demonstrated with spoken instead of written language.

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