Newly trained lexical categories produce lateralized categorical perception of color

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Contributed by Paul Kay, April 25, 2010 (sent for review March 31, 2010)

Linguistic categories have been shown to influence perceptual discrimination, to do so preferentially in the right visual field, to fail to do so when competing demands are made on verbal memory, and to vary with the color-term boundaries of different languages. However, because there are strong commonalities across languages in the placement of color-term boundaries, the question remains open whether observed categorical perception for color can be entirely a result of learned categories or may rely to some degree on innate ones. We show here that lateralized color categorical perception can be entirely the result of learned categories. In a visual search task, reaction times to targets were faster in the right than the left visual field when the target and distractor colors, initially sharing the same linguistic term (e.g., "blue"), became between-category colors after training (i.e., when two different shades of blue had each acquired a new name). A control group, whose conditions exactly matched those of the experimental group except that no new categories were introduced, did not show this effect, establishing that the effect was not dependent on increased familiarity with either the color stimuli or the task. The present results show beyond question that lateralized categorical perception of color can reflect strictly learned color categories, even artificially learned categories that violate both universal tendencies in color naming and the categorization pattern of the language of the subject.

category learning | Whorf hypothesis | nature versus nurture | linguistic relativity

A long-standing "Whorfian" debate over the relation between language and thought has gained momentum in recent years with an increasing number of studies demonstrating the involvement of linguistic information in categorical perception of color (1–18).* For example, speakers of English judge colors that straddle the English category boundary between green and blue to be less similar than do speakers of Tarahumara, a Uto-Aztecan language of Mexico that uses a single word for these colors (1). Unlike English, Russian makes a distinction between lighter blues (*goluboy*) and darker blues (*siniy*), and Russian speakers are faster, compared with English speakers, in discriminating two colors when they fall into different categories, one *goluboy* and the other *siniy*, than when they belong to the same category (6). More recent findings provide a different perspective, suggesting that language is disproportionately engaged in the discrimination of colors presented in the right visual field (RVF) as compared with the left visual field (LVF) (5, 7, 8, 10, 11). Specifically, discrimination of colors from two different lexical categories (e.g., a green among blues) is faster than discrimination of colors from the same lexical category (e.g., one green among tokens of a different green), but only (or predominantly) when the between-category colors are presented in the RVF. [Significant color categorical perception (CP) has also been found in the LFV (7, 8) but it is always weaker than in the RVF. Because it is associated with longer response times, this effect has been argued to result from transcallosal transfer or in some cases scanning (7, 14, 18).] This RVF advantage arises from the activation of language regions of the left cerebral hemisphere (13, 14), to which the RVF projects, where the lexical distinction of colors may exaggerate or reduce the perceptual difference (19, 20). In sum, there is a lateralized Whorf effect: linguistic categories filter some, but not all, perceived inputs (16–18).

Earlier results have shown that lateralized color CP varies according to the location of category boundaries in individual languages (5–8) and disappears when verbal interference, but not comparable nonverbal interference, is induced by a concurrent task (5, 6). On the other hand, color-term boundaries tend to be similar across languages (21–26), and prelinguistic infants and toddlers display CP at color-term boundaries that accord well with universal tendencies in color naming (10, 11, 27). Moreover, most of the color CP experiments have concentrated exclusively or largely on the blue/green boundary, present of course in English, but also widespread in the world. Therefore, there is uncertainty regarding the degree to which color CP, as so far observed, reflects learned versus presumably innate categories, especially because linguistic and seemingly innate color categories tend to coincide. It has been shown that perceptual discrimination can be trained to new category distinctions that will then produce observable CP effects (19, 28, 29). Özgen and Davies have shown specifically that category effects can be trained in the color domain, although they did not train explicitly verbal categories (30). If a lateralized category effect can be shown to occur for experimentally trained verbal categories, it will follow that the lateralized Whorf effect can occur even when the categories involved violate both universal tendencies in color naming and those of the language of the subjects. Such a finding will reinforce the behavioral evidence reviewed above, as well as the corroborating event-related potential (ERPs) and fMRI evidence (13, 14, 31), that color CP, lateralized to the left hemisphere and suppressible by verbal interference, is a language-dependent ("Whorfian") phenomenon.

Using an intensive training method to teach subjects new linguistic terms for colors originally from the same lexical cate-

Author contributions: K.Z., L.M., P.K., V.P.Y.K., T.N.M.I., and L.H.T. designed research; K.Z., L.M., and V.P.Y.K. performed research; K.Z. analyzed data; and K.Z., L.M., P.K., V.P.Y.K., T.N.M.I., and L.H.T. wrote the paper.

The authors declare no conflict of interest.

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*We follow common usage in employing the expression "categorical perception" to denote the findings of the experiments cited here that establish category effects in color discrimination. We do not thereby assume a position on whether these effects will ultimately be found to lie on the perception or the response side. In particular, several of the studies cited below as establishing categorical perception demonstrate category effects against a baseline measure that is, at least nominally, equally spaced perceptually, and which would therefore already be adjusted for categorical perception effects if it is indeed perceptually equally spaced in the task setting. However, the present study, like some prior studies (4, 5, 7, 13, 14), is not dependent on the spacing of the stimuli because the differential effects in the two visual fields (or two cerebral hemispheres) demonstrate that whatever the "true" spacing of the stimuli may be, the RFV/LH is more sensitive to category difference than the LVF/RH in speaking adults.

 www.pnas.org/cgi/doi/10.1073/pnas.1005669107

gory, we demonstrate such a definite cause-effect relationship. A version of the visual search task employed in the original lateralized Whorf study (5) was administered to 31 adults divided into two groups, closely matched for age and sex. Each stimulus display included colors selected from a set of four (Fig. 1 *A* and *B*), forming a ring of colored squares surrounding a central fixation point (Fig. 1*C*). All of the squares were of the same color except the target. Following central fixation, participants were shown the ring of colors and asked to indicate whether the target was on the left (LVF) or right (RVF) side of the circle, by making a speeded button-press response with the corresponding hand.

Group 1 (experimental group, $n = 18$ Mandarin Chinese speakers) performed the visual search task twice, once before and once after training. The four colors, which we designate green 1 (G1), green 2 (G2), blue 1 (B1), and blue 2 (B2), form a graded series from green to blue. The boundary between 绿 "green" and 藍 "blue" falls between G2 and B1 (Fig. 1*A*). Before the training session, the target and distractor colors were either from the same lexical category (i.e., B1B2 or G1G2; "within category") or from distinct lexical categories (i.e., G2B1; "between category"). In this manner, two variables were manipulated in the before-training search task: the categorical relationship between the target and distractor colors (between vs. within category) and the visual field of the target (LVF vs. RVF) (Fig. 1*C*). After completion of the first visual search task, group 1 received intensive training in assigning colors G1, G2, B1, and B2, respectively, to four new lexical categories, named with meaningless monosyllables: *áng*, *sòng*, *duān*, and *kěn*. Thus, the within-category colors before training became between-category colors after training, although the colors themselves did not change. The training involved six individual sessions (total training time of 3 h), spread over 3 days, and included three activities: listening, naming, and matching. For the listening task, subjects simply heard each new word while viewing the appropriate color. In the naming task, while a color was displayed the subject was required to give the new color name; immediate feedback was provided. The matching task required subjects to decide whether the sound they heard was the new name for the color viewed on the computer screen. Again, immediate feedback was given. Participants successfully learned the new categories within the training period, as discussed below and summarized in Fig. 2.

After the training period, subjects performed the visual search task again (Fig. 1*C*), but now every target color belonged to a different lexical category from the accompanying distractors. This training task is different from the perceptual learning paradigm of categorical color perception (28–30) in that we explicitly assigned a new linguistic term to each of the four stimulus colors: A, B, C, and D. Our interest is focused on subjects' responses to the color pairs that had been within-category before training but became between-category after training. The goal was to determine whether pairs of colors that were within-category before training would be discriminated faster after training had assigned them to distinct linguistic categories, and if so whether the difference in speed of discrimination would be greater in the RVF than the LVF, revealing a lateralized Whorf effect on newly learned categories.

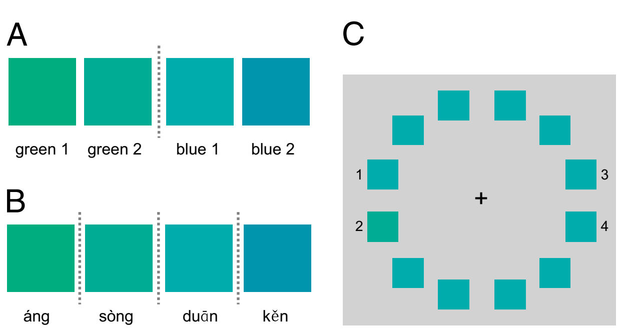

Fig. 1. Experimental materials. (*A*) Printed-rendered versions of the four colors used with their ordinary names. (*B*) Printed-rendered versions of the four colors used with their new names to be acquired by the subjects. (*C*) Sample display for the visual search task. The target occupied any of the four positions (position 1, 2, 3, or 4). This example shows a between-category LVF pair.

To exclude the possibility that any observed difference between pre- and posttraining trials might be the result of a gain in familiarity with the stimuli or task demands, we included group 2 (a control group, $n = 13$), who also performed a second visual search task, but whose intersearch-task experience consisted simply in performing the identical tasks that the experimental group did in learning the new color words using only the original Mandarin color terms (i.e., 绿 "green" and 藍 "blue"). This practice regime simply gave subjects redundant exposure to color terms they already knew. (For the reader's convenience, we use the word "training" in connection with the experimental group and "practice" in connection with the control group.)

Results and Discussion

Experimental Group. Trials in which the participant pressed the wrong key or in which the reaction time (RT) was >2 SD from the grand mean were excluded. Response accuracies were very high (>94% in all conditions) and did not show any statistically significant differences between conditions, so our analysis focused on RTs, as illustrated in Fig. 3.

We first verified that there was a significant lateralized Whorf effect in color search before training. Using a 2 (visual field: LVF vs. RVF) × 2 (category type: within- vs. between-category) ANOVA (Fig. 3*A*), we found a highly reliable category effect, with between-category RTs faster than within-category RTs (455 ms vs. 476 ms), $F(1,17) = 38.13$, $P < 0.001$. Similar to Gilbert et al. (5), there was no significant effect of visual field (468 ms vs. 462 ms). Most crucially, the interaction of the two variables was significant, $F(1,17) = 8.32$, $P < 0.01$, with RVF between-category RTs being the shortest.

For between-category trials, RTs were faster when the target was displayed in the RVF than when it was displayed in the LVF [447 ms vs. 463 ms; $t(17) = -3.11$, $P < 0.007$]. For the within-category trials, there was no reliable difference between the RVF and the LVF [478 ms vs. 474 ms; $t(17) = 0.67$, $P > 0.5$].

Critically, we compared RTs for within-category vs. between-category conditions within each visual field. For RVF targets, RTs in the between-category condition (447 ms) were 31 ms faster than in the within-category condition [447 ms vs. 478 ms; $t(17) = -4.98$, $P < 0.001$]. For LVF targets, RTs in the between-category condition were 11 ms faster than in the within-category condition [463 ms vs. 474 ms, which was also reliable, $t(17) = -4.24$, $P < 0.002$]. The category effect for RVF targets (31 ms), however, was significantly larger than the category effect for the LVF target (11 ms), $t = 2.88$, $P < 0.01$, consistent with the aforementioned interaction. In a nutshell, this pattern of pretraining data is consistent with previous findings, confirming the left-lateralized Whorf effect; that is, the CP effect for normal language users is stronger in the RVF than the LVF.

To determine whether training on new categories modulates discrimination differently in the two visual fields, we compared RTs across visual fields before and after training (Fig. 3 *B* and *C*). Following training, category pairs that had been within-category, (G1, G2; "green") and (B1, B2; "blue"), became between-category: G1, *áng*; G2, *song*; B1, *duān*; B2, *kěn*. Fig. 2 illustrates subjects' average accuracies for acquiring the new color terms in each of the six training sessions, indicating that after even a short training session, subjects readily control the four newly acquired linguistic categories. The comparison between the RTs before and after

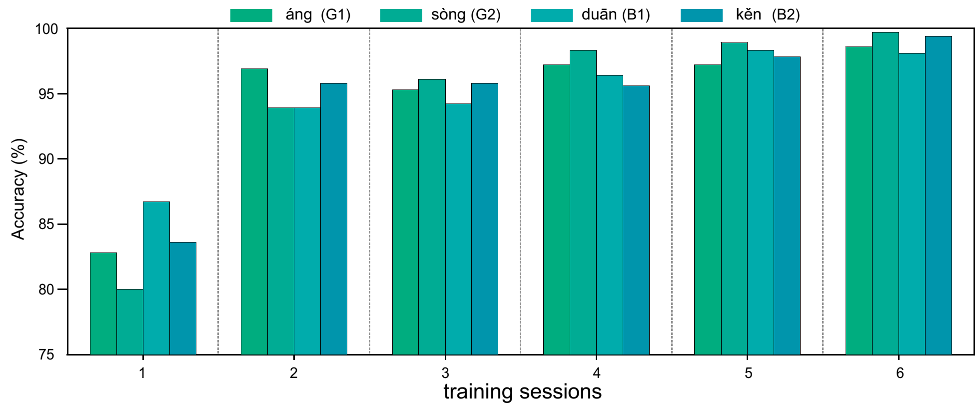

Fig. 2. Subjects' average recognition accuracies to the four colors with new names during the training phases.

training for stimulus pairs that were within-category before and between-category after training is shown in Fig. 3*B*.

The 2 (visual field: LVF vs. RVF) × 2 [training-type: trained (= between) vs. untrained (= within)] ANOVA of subjects' performances on color search revealed that there was a significant main training effect (i.e., linguistic category effect), with RTs in the posttraining conditions 40 ms faster than in the pretraining conditions (436 ms vs. 476 ms), $F(1,17) = 24.10$, $P < 0.001$. The main effect of visual field was again not significant, $F(1,17) = 1.75$, $P > 0.2$. Importantly, there was a significant training × visual field interaction, $F(1,17) = 6.58$, $P < 0.02$, resulting from the fact that RVF posttraining between-category RTs were the shortest. Although there had been no reliable difference between the RVF and the LVF for within-category pairs before training (as described above: 478 ms vs. 474 ms), following training RTs were significantly faster in the RVF than in the LVF [430 ms vs. 442 ms, $t(17) = -3.01$, $P < 0.009$]; that is, after these pairs had become between-category. For RVF targets, RTs in the posttraining between-category condition were 48 ms faster than in the pretraining within-category condition (430 ms vs. 478 ms), $t(17) = -5.20$, $P < 0.001$. For LVF targets, RTs in the between-category condition (posttraining) were 32 ms faster than in the within-category condition (pretraining), $t(17) = -3.89$, $P < 0.002$. Still, there was a significant lateralized Whorfian effect (48 ms vs. 32 ms), $t = 2.56$, $P < 0.02$.

To further examine whether there was a difference in category effect because of training in the two visual fields, we also compared RTs for the colors that were between-category both before and after training (Fig. 3*C*). Overall, training resulted in faster RTs, $F(1,17) = 10.01$, $P < 0.006$, but there were RVF advantages both before [447 ms vs. 463 ms, $t(17) = -3.11$, $P < 0.007$] and after training [418 ms vs. 435 ms, $t(17) = -3.69$, $P < 0.003$]. The effect size (16 ms before training and 17 ms after training) was not modulated by training, as indicated by a nonsignificant visual field × training interaction ($F < 1$).

Control Group. To rule out the possibility that the claimed Whorfian effect after training in the experimental group might stem from increased familiarity with either the stimuli or task demands, we tested 13 subjects in a control group. These subjects performed the search task twice but, in the place of training on new categories, they underwent a practice session that employed exactly the same procedures as in the training session of the experimental group but simply used the existing color names, rather than introducing new names. (All subjects' naming accuracies during each of the practice sessions were above 99%, indicating sufficient attention.) The search task the control subjects performed (twice) was identical to the search tasks performed by the experimental group. As shown in Fig. 4, the main effect of category type (within vs. between) and the interaction of category × visual field were significant both for the prepractice color search [$F(1,12) = 21.72$, $P < 0.001$ for the category effect, and $F(1,12) = 4.87$, $P < 0.05$ for the interaction] and for the postpractice color search [$F(1,12) = 32.46$, $P < 0.001$ for the category effect, and $F(1,12) = 5.73$, $P < 0.04$ for the interaction]. The

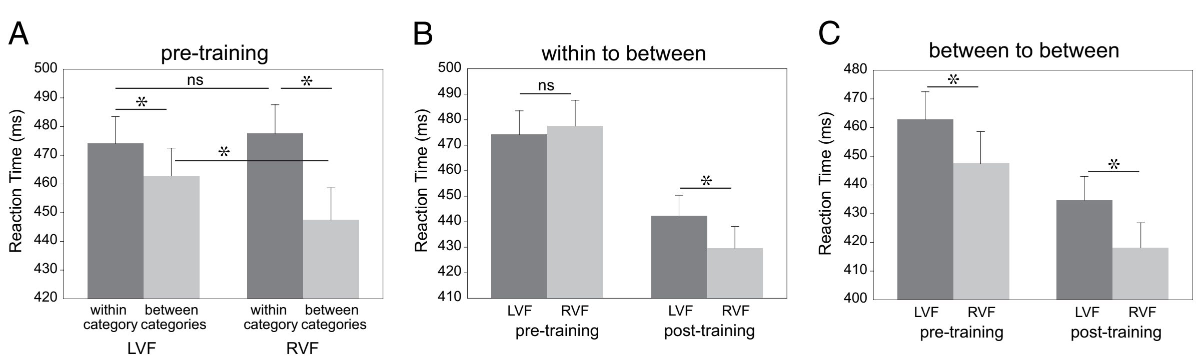

Fig. 3. Behavioral performance of subjects in the experimental group. (*A*) In the pretraining color search condition, a highly significant category effect was found, with between-category RTs faster than within-category RTs (455 ms vs. 476 ms). There was no significant effect of visual field (468 ms vs. 462 ms). Crucially, the interaction of the two variables was significant, with RVF between-category RTs being the shortest. (*B*) Training effects for within-category colors at the pretraining phase, which became between-category colors after training. Before training, there is no reliable VF difference for within-category targets. After training, former within-category pairs that have become between-category pairs are now identified faster in the RVF than in the LVF. (*C*) Training effects for between-category colors at both pre- and posttraining phases. Between-category targets are identified faster in RVF than in LVF both before and after training. Error bars indicate SEM. Asterisk (*) indicates a significant response difference at $P < 0.05$.

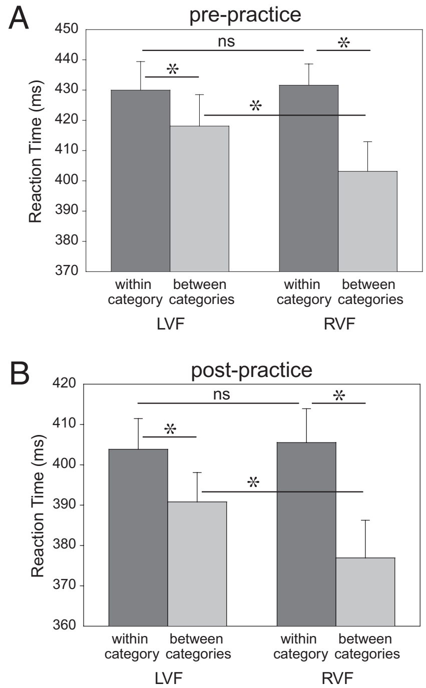

Fig. 4. Behavioral performance of subjects in the control group. (*A*) Prepractice and (*B*) postpractice. Error bars indicate SEM. Asterisk (*) indicates a significant response difference at $P < 0.05$.

category effect for the RVF targets was much greater than for the LVF targets (28 ms vs. 12 ms at the prepractice session, and 29 ms vs. 13 ms at the postpractice session), suggesting that the left-lateralized Whorf effect was not altered by general task familiarity in this study. Crucially, we considered the control subjects' performance to colors that were within-category at both the prepractice session (430 ms for LVF colors and 432 ms for RVF colors) and the postpractice phase (404 ms for LVF colors and 406 ms for RVF colors). These are the colors whose categories were changed by training in the experimental group, and which showed the lateralized Whorf effect after the change. The main effect of practice was significant, $F(1,12) = 36.07$, $P < 0.001$. The main effect of visual field and the interaction of practice × visual field both failed to approach significance, Fs < 1. Thus, practice itself did not generate a lateralized Whorf effect.

In summary, a standard lateralized Whorf effect (faster discrimination for cross-category pairs in the RVF) was established on a rapid discrimination task, replicating previous findings (4, 5, 7, 8, 10, 11, 13, 14). Two green and two blue stimuli were used. Mandarin Chinese contains the words 绿 and 藍 , which translate well the English words "green" and "blue," respectively. An experimental group was trained to assign each of the four stimuli to a separate verbal category named by an introduced nonsense syllable. A control group was subject to parallel practice on the original categories without introduction of the new categories or category words. Both groups were then subjected to the rapid discrimination task a second time. The experimental group showed an RVF-lateralized decrease in RT for the color pairs that were within-category before training and between-category after training. The control group, which was not taught the new categories but was otherwise subjected to the same practice procedure as the experimental group, showed no such effect on these pairs, confirming that the lateralized category effect in the experimental group was not caused by increase in familiarity with the stimuli or the task demands. For the experimental group, category pairs that lay within a category before training behaved after training like the cross-category pairs they had become: specifically showing the lateralized Whorf pattern of faster RTs for between- than within-category pairs in the RVF only (where the pairs G1G2 and B1B2 were within before training and between after training). Because the new categories were artificially taught and the newly taught category boundaries agreed neither with those of the native language of the subjects nor with any category boundaries that may be found in numerous (probably in any) natural languages, this particular Whorfian effect can be wholly attributed to nurture rather than nature, demonstrating the possibility that Whorfian effects can be imposed by cultural constraint independent of any support from possible inborn tendencies to assign category boundaries to restricted regions of color space.

Materials and Methods

Subjects. Thirty-one adults who were Beijing college students (21 males and 10 females; mean age = 24.4 years, SD = 1.7 years) participated in this experiment. They were tested with the Ishihara test for color vision deficiency and found normal; none had any history of neurological or psychiatric illness. All subjects were strongly right-handed. Participants were divided into two groups: the experimental group ($n = 18$), whose members received intensive training to acquire new names of colors (Fig. 1 *A* and *B*), and the control group ($n = 13$), whose members performed the same tasks as were required in the experimental group, but associating the stimulus colors with their existing, standard names rather than introducing new lexical categories.

Stimuli and Experimental Design. The stimuli were presented on a 19-inch computer screen at a viewing distance of 90 cm. The RGB values of the four colors used in the present study were as follows (Fig. 1*A*): G1 = 0, 171, 129; G2 = 0, 170, 149; B1 = 0, 170, 170; B2 = 0, 149, 170. The brightness and saturation values were adjusted to make them equal, based on the independent judgments of four observers. The RGB values for the background were 210, 210, and 210. The CIEL*u*v* interpair distances are (G1,G2) = 16.3 ΔE, (G2,B1) = 17.48 ΔE, (B1,B2) = 19.47 ΔE. The mean within-category distance, 17.89 ΔE, slightly exceeds the between-category (G2,B1) distance, 17.48 ΔE.

The experimental design consisted of two visual search tasks at the first and fifth days. Between these measurements, subjects completed training (experimental group) or practicing (control group) sessions on 3 consecutive days. One additional 5-min familiarization session was administered to each subject immediately before the second visual search task on fifth day. Before the experiment, all subjects were given a blue–green lexical boundary test. On each trial, a square stimulus (one of the four colors, G1, G2, B1, and B2) was presented centrally on a gray background for 200 ms, followed by a 1,000-ms interval. Subjects indicated whether the stimulus was green or blue by pressing one of two keys, corresponding to the Mandarin Chinese words 绿 "green" and 藍 "blue," respectively. Each stimulus was presented 10 times in a total of 40 randomized trials. All subjects identified over 95% of the presentations of both G1 and G2 as "green" and of both B1 and B2 as "blue," so no subjects' results were discarded.

Visual Search Task. A visual search paradigm similar to the one in Gilbert et al. (5) was used. During each trial, a ring of 12 colored squares surrounding the fixation marker were presented simultaneously for 200 ms against a gray background (Fig. 1*C*), preceded by a fixation screen displaying only the centrally located fixation cross "+". The inner edge of the target color was presented 3.9° to the right or to the left of the fixation cross. Hence, the target positions were separated by a visual angle of 7.8°. Subjects indicated whether the target was on the left or right side of the circle by making a button-press response with the corresponding hand, as quickly and as accurately as possible. The duration of the fixation screen was 1,800 ms. There were six target–distractor pairs, formed by using all single-step, pairwise combinations of the four colors (three pairs: G1G2, B1B2, and G2B1 for the pre- and postpractice phases of the control group and for the pretraining test of the experimental group) and having each member of a pair serve once as target and once as distractor. The target occupied any of the four positions (position 1, 2, 3, and 4 in Fig. 1*C*), and there were 24 possible stimulus configurations. Each subject completed two 216-trial blocks, with each stimulus configuration appearing at random, once per block. The experimental and the control groups received the identical stimulus pairs in the posttraining or postpractice test.

Training Phase for the Experimental Group. Four made-up Chinese monosyllables were assigned to the four stimulus colors: *áng* for G1, *sòng* for G2, *duān* for B1, and *kěn* for B2. They are phonologically unrelated to the original color set. The training received by the subjects in the experimental group involved six individual sessions, two each day. Each session lasted 30 min. In each trial, one of the stimulus colors was displayed in the center of the screen for 1,000 ms, followed by a blank screen interstimulus interval for 1,000 ms. Three training tasks were used: listening, naming, and matching. In the listening task, the sound corresponding to the new color name was presented along with the presentation of the colored square. For the naming task, subjects had to report the new color name of the presented colored square and their recognition performance (percent-correct naming) was recorded. Auditory feedback with correct color name was given. In the matching task, the sound of a randomly chosen color name was presented along with visual presentation of the colored square. The subject's task was to judge, by choosing "yes" or "no" on a printed form, whether the sound they heard matched the new name for the color viewed on the computer screen. Immediate feedback was given.

Practice Phase for the Control Group. The stimuli and procedures for the practice phase of the control group were identical to those of the training phase of the experimental group, with the sole exception that only the original color names were used: 绿 "green" for G1 and G2 and 藍 "blue" for B1 and B2. Naming accuracy in every practice session exceeded 99%, indicating that subjects' attention was maintained throughout.

ACKNOWLEDGMENTS. We thank Sandra Fung and Anna Huang for assistance with stimulus preparation and computer programming, and Dong Daojing, Wei Zhou, and Ding Wen for help with testing subjects. This research was supported by a 973 grant from the National Strategic Basic Research Program of the Ministry of Science and Technology of China (2005CB522801, 2005CB522802), US National Science Foundation Grant 0418404, Guangdong Natural Science Foundation on Task for Research Group 06200524, National Natural Science Foundation of China Grants 30621004 and 90820307, Chinese Academy of Sciences Grants KSCX2-YW-R-122 and KSCX2-YW-R-259, and the University of Hong Kong.

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