

# Learning new color names produces rapid increase in gray matter in the intact adult human cortex

Veronica Kwok<sup>a,b,1</sup>, Zhendong Niu<sup>c,1</sup>, Paul Kay<sup>d,e,2</sup>, Ke Zhou<sup>f</sup>, Lei Mo<sup>g</sup>, Zhen Jin<sup>h</sup>, Kwok-Fai So<sup>a,i,j</sup>, and Li Hai Tan<sup>a,b,2</sup>

<sup>a</sup>State Key Laboratory of Brain and Cognitive Sciences, <sup>b</sup>Department of Linguistics, and <sup>i</sup>Department of Anatomy, University of Hong Kong, Hong Kong, China; <sup>c</sup>School of Computer Science and Technology, Beijing Institute of Technology, Beijing 100081, China; <sup>d</sup>Department of Linguistics, University of California, Berkeley, CA 94720; <sup>e</sup>International Computer Science Institute, Berkeley, CA 94704; <sup>f</sup>State Key Laboratory of Brain and Cognitive Science, Institute of Biophysics, Chinese Academy of Sciences, Beijing 100101, China; <sup>g</sup>Center for the Study of Applied Psychology, South China Normal University, Guangzhou 510631, China; <sup>h</sup>MRI Division, Beijing 306 Hospital, Beijing 100101, China; and <sup>j</sup>Joint Laboratory for Brain Function and Health, Jinan University and The University of Hong Kong, Guangzhou 510632, China

Contributed by Paul Kay, February 28, 2011 (sent for review February 2, 2011)

The human brain has been shown to exhibit changes in the volume and density of gray matter as a result of training over periods of several weeks or longer. We show that these changes can be induced much faster by using a training method that is claimed to simulate the rapid learning of word meanings by children. Using whole-brain magnetic resonance imaging (MRI) we show that learning newly defined and named subcategories of the universal categories green and blue in a period of 2 h increases the volume of gray matter in V2/3 of the left visual cortex, a region known to mediate color vision. This pattern of findings demonstrates that the anatomical structure of the adult human brain can change very quickly, specifically during the acquisition of new, named categories. Also, prior behavioral and neuroimaging research has shown that differences between languages in the boundaries of named color categories influence the categorical perception of color, as assessed by judgments of relative similarity, by response time in alternative forced-choice tasks, and by visual search. Moreover, further behavioral studies (visual search) and brain imaging studies have suggested strongly that the categorical effect of language on color processing is left-lateralized, i.e., mediated by activity in the left cerebral hemisphere in adults (hence “lateralized Whorfian” effects). The present results appear to provide a structural basis in the brain for the behavioral and neurophysiologically observed indices of these Whorfian effects on color processing.

neuro-plasticity | brain development | Whorf hypothesis | anatomy

Research on the adult animal brain has demonstrated experience-induced cortical structural changes and the relevant time scales at the cellular and synaptic level (1–11). In normal human adults, neuroimaging studies have shown structural plasticity (indexed by gray matter changes) in response to the acquisition of a new skill obtained by training over periods ranging from weeks (12) to years (13–17). Although these findings in themselves constitute a challenge to the traditional view that the anatomical structure of the intact adult human cortex cannot be altered, the degree of structural plasticity at this macroscopic level remains unknown.

In this study, we show that learning artificially defined and named subcategories of the universal color names green and blue (18, 19) for 2 h increases the volume of gray matter in V2/3 of the visual cortex. We used an intensive training method to teach subjects ( $n = 19$ , females = 10, mean age = 20.1 y) to map new nonsense terms onto newly created color categories (two shades of blue and two shades of green). A similar training procedure was used by Markson and Bloom (20) to simulate the “fast-mapping” phenomenon, in which children (and adults) learn new word–object associations after just a few exposures. Four visibly but not lexically distinguishable colors, which we originally designated green 1 (G1), green 2 (G2), blue 1 (B1), and blue 2 (B2) were taught to subjects to exemplify, respectively, four new lexical categories, named with meaningless Mandarin monosyllables: *áng*, *sòng*, *duān*, and *kèn* (21). Thus, the within-category

colors before training became the between-category colors after training, although the colors themselves did not change (Fig. 1).

## Results and Discussion

The training involved five individual sessions (total training time = 1 h 48 min), spread over 3 d and included three activities (“listening,” “naming,” and “matching”) in sessions 1 and 2 and two activities (“naming” and “matching”) in sessions 3–5. For the listening task, subjects simply heard each new word while viewing the appropriate color. In the naming task, a color was displayed and 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 displayed on the computer screen. Again, immediate feedback was given. Participants successfully learned the new category names in the course of the training phase, as illustrated in Fig. 2.

We collected high-resolution structural 3D magnetic resonance imaging (MRI) images from these adult subjects before and after they had acquired the new color names. An established (22) and widely used whole-brain assessment technique (12–14, 23, 24), voxel-based morphometry (VBM), was used to analyze the MRI anatomical images and determine possible brain structure differences indexed by gray matter volume. The two brain scans (pre- and posttraining) showed a significant difference in the V2/3 ( $X = -10$ ,  $Y = -77$ ,  $Z = 3$ ;  $P < 0.005$  uncorrected;  $Z = 3.58$ ) and cerebellum ( $X = 13$ ,  $Y = -75$ ,  $Z = -38$ ;  $P < 0.005$  uncorrected;  $Z = 3.86$ ) (Fig. 3). The volume of gray matter significantly increased in these regions following the less-than-2-h training. Because V2/3 is shown to be involved in color perception (25–29), a small volume correction (SVC) analysis procedure was applied. We found that the gray matter difference in this region was significant at  $P < 0.05$  with family-wise error corrected (FWE) after the SVC with a 20-mm sphere around a peak activation ( $X = -16$ ,  $Y = -64$ ,  $Z = 9$ ) identified in the literature (26). Thus, this region survived the whole-brain analysis threshold at  $P < 0.005$  (uncorrected) and the small volume correction with  $P < 0.05$  with FWE corrected.

This result provides information regarding the effect of learning on (*i*) the rapid formation of new cortical gray matter as a result of experience and (*ii*) on the function of the brain in processing color stimuli.

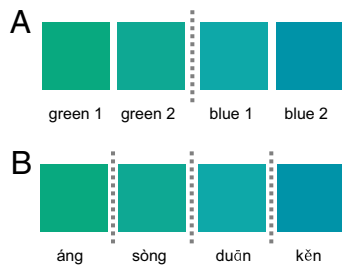
When considering the effect of learning on the rapid formation of new cortical gray matter, past research on experience-induced cortical changes has focused on motor-task learning (1, 2, 12) and on synaptic structures (1, 2). The present study, using a visual fast-mapping task shown to mirror children’s rapid

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

The authors declare no conflict of interest.

<sup>1</sup>V.K. and Z.N. contributed equally to this work.

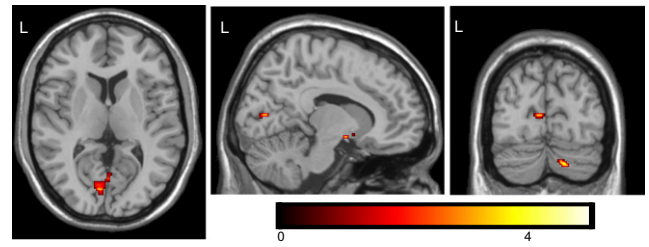
<sup>2</sup>To whom correspondence may be addressed. E-mail: paulkay@berkeley.edu or tanlh@hku.hk.



**Fig. 1.** Colors used in the course of the training phase. (A) Print-rendered versions of the four colors used with their ordinary names. (B) Print-rendered versions of the four colors used with their new names to be acquired by the subjects.

learning processes (20), has both extended prior work to another form of learning and memory (30) and shown that cortical changes can be induced in a training period significantly shorter than any previously established. These results may also be considered as providing a structural basis for previously observed functional brain changes (shown by functional MRI) during category learning (of dot patterns) (32). The time course of cortical changes in gray matter in the human adult brain remains to be established (33), and the question of how cortical changes at the macroscopic and the synaptic levels are related to each other is still to be answered. Although there is still much to be learned on all of these issues, the present study strengthens the proposition that the intact human adult brain is structurally more plastic than previously believed.

With regard to color perception and processing in particular, previous work has shown that differences between languages in the boundaries of named color categories predictably affect the regions of the hue spectrum at which “categorical perception” occurs, as assessed in a variety of different ways. When speakers of English and of a language (Tarahumara, Uto-Aztecan family, Mexico) that makes no lexical distinction between green and blue were asked to judge relative similarities of color chips in an odd-man-out “triads” format, English-speaking participants were found to exaggerate the perceived distance between colors spanning the green/blue boundary relative to Tarahumara speakers and to perceptual separation measured in just-noticeable differences (34). Parallel results were found in a study comparing three languages: English, Berinmo (Sepik family, Papua New Guinea), and Himba (Bantu family, Namibia) (35). In several studies measuring response times in alternative forced-choice tasks (e.g., 34), it has been found that colors spanning a lexical boundary present in one language but not in another are more quickly discriminated in the former language. In studies using visual search (e.g., 36, 37), it has been revealed that target colors that differ in lexical category from a field of distracters are more quickly identified than targets



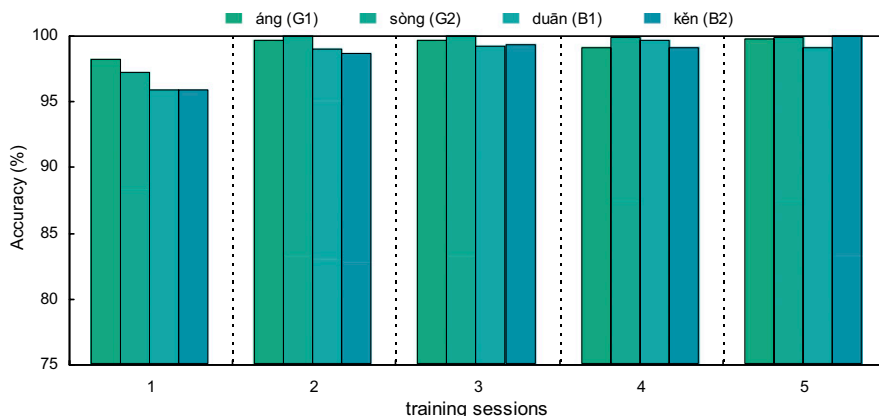
**Fig. 3.** Differences in gray matter volume between post- and pretraining scans, as illustrated by images from axial (Left), sagittal (Center), and coronal (Right) views. The region in the cerebral cortex surviving a whole-brain-based analysis ( $P < 0.005$  uncorrected) is V2/3 ( $X = -10$ ,  $Y = -77$ ,  $Z = 3$ ;  $Z = 3.58$ ). One area in the cerebellum ( $X = 13$ ,  $Y = -75$ ,  $Z = -38$ ;  $P < 0.005$  uncorrected;  $Z = 3.86$ ) also shows a volumetric difference. A small volume correction (20-mm) analysis of V2/3 indicated that the difference was significant at  $P < 0.05$  FWE.

of equal perceptual separation that belong to the same lexical category as the distracters. It has further been established that these and comparable effects in *lateralized* visual search are mediated by activity in the left hemisphere (in adults, but not in infants or prelinguistic toddlers) (31, 38–41, among others) and probably by specific language areas within the left hemisphere (26). Comparable results with unfamiliar laboratory-taught color categories have been observed in behavioral studies (21, 42). The current results may be understood as beginning to provide a structural basis in the brain for the behavioral and neurophysiologically observed indices of these “Whorfian” effects on color processing.

## Materials and Methods

**Subjects.** Nineteen adults, who were Beijing university students (9 males and 10 females), participated in this experiment. They were tested with the Ishihara test for color vision deficiency and found to be normal; none had any history of neurological or psychiatric illness. All participants received training to acquire new names for the four colors (Fig. 1 A and B).

**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. 1A): G1 = 0, 171, 129; G2 = 0, 170, 149; B1 = 0, 170, 170; B2 = 0, 149, 170. The corresponding CIEL\*u\*v\* values were as follows: G1 = 62.2, -52.3, 23.0; G2 = 62.4, -50.4, 6.8; B1 = 63.1, -48.8, -10.5; and B2 = 56.5, -41.5, and -27.3. The RGB values for the background were 210, 210, and 210, and the constant CIEL\*u\*v\* value was 84.2, 0, 0. The CIEL\*u\*v\* interpair distances were (G1, G2) = 16.3ΔE, (G2, B1) = 17.5ΔE, and (B1, B2) = 19.5ΔE. The brightness and saturation values were adjusted to make them appear equal on the basis of the independent judgments of four observers. 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



**Fig. 2.** Subjects' average recognition accuracies of the four colors with new names during the training phase.

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 蓝 “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 subject’s results was discarded.

**Training Phase for the Experimental Group.** Four made-up Chinese monosyllables were assigned to the four stimulus colors: *āng* for G1, *sòng* for G2, *duān* for B1, and *kèn* for B2. They are phonologically unrelated to any other Mandarin words for colors. The training received by the subjects involved five individual sessions, spread over 3 d. Sessions 1 and 2 contained three activities: listening, naming, and matching, each session lasting for 24 min. Sessions 3–5 contained only naming and matching, each session lasting for 20 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 of 1,000 ms. In the listening task, the sound corresponding to the new color name was presented along with 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 (percentage correct naming) was recorded. Auditory feedback with the correct color name was given. In the matching task, a randomly chosen color name was presented aurally along with visual presentation of one of the four colored squares. The subjects’ task was to judge, by choosing “yes” or “no” on a printed form, whether the sound they heard matched the new name for the displayed color. Immediate feedback was given.

**MRI Acquisition.** MRI scans were performed on a 3-T scanner (TRIO Tim; Siemens) at Beijing 306 Hospital. Three-dimensional, high-resolution anatomical scans were acquired by using an MPAGE (magnetization prepared rapid gradient echo) sequence (echo time = 3.01 ms; repetition time = 2,300 ms; flip angle = 9°; 1 NEX scan). A total of 176 coronal T1-weighted images

with a field of view of 256 × 240 mm and voxel sizes of 1 × 1 × 1 mm were produced.

**VBM Analysis.** VBM analysis was performed using the DARTEL in SPM8. Images were bias-corrected, tissue-classified, and registered using linear (12-parameter affine) and nonlinear transformations (warping) within a unified model (43). Subsequently, analyses were performed on gray matter (GM), which were multiplied by the nonlinear components derived from the normalization matrix to preserve actual GM values locally (modulated GM volumes). Importantly, the segments were not multiplied by the linear components of the registration to account for individual differences in brain orientation, alignment, and global size. Finally, the modulated volumes were smoothed with a Gaussian kernel of 8 mm full width at half maximum.

For the statistical analysis, regional differences in gray matter volume were tested by paired *t* test. To avoid possible edge effects between different tissue types, we excluded all voxels with GM or white matter values of 0.2 (absolute threshold masking). We applied a threshold of  $P < 0.005$  with an extent of 40 voxels across the whole brain. Brain regions were estimated from Talairach and Tournoux (44) after adjustments for differences between MNI and Talairach coordinates. An SVC (20-mm) analysis procedure was applied to the region (V2/3), previously shown to be involved in color vision (25–29), indicating that the gray matter difference in this region was significant at  $P < 0.05$  FWE after the SVC with a 20-mm sphere around a peak activation ( $X = -16$ ,  $Y = -64$ ,  $Z = 9$ ) identified in the literature (26).

**ACKNOWLEDGMENTS.** We thank Sandra Fung and Anna Huang for assistance with stimulus preparation and computer programming; Guiping Xu, Dong Daojing, Wei Zhou, Ding Wen, and Zhentao Zuo for help with conducting the experiment; and Wai Ting Siok and Susan Whitfield-Gabrieli for advice on image analysis. This research was supported by a 973 Grant from the National Strategic Basic Research Program of the Ministry of Science and Technology of China (2005CB522802), by National Science Foundation Grant 0418404, by the Guangdong Natural Science Foundation on Task for Research Group 06200524, by the National Natural Science Foundation of China 2011, and by the University of Hong Kong.

- Yang G, Pan F, Gan WB (2009) Stably maintained dendritic spines are associated with lifelong memories. *Nature* 462:920–924.
- Xu T, et al. (2009) Rapid formation and selective stabilization of synapses for enduring motor memories. *Nature* 462:915–919.
- Grutzendler J, Kasthuri N, Gan WB (2002) Long-term dendritic spine stability in the adult cortex. *Nature* 420:812–816.
- Trachtenberg JT, et al. (2002) Long-term in vivo imaging of experience-dependent synaptic plasticity in adult cortex. *Nature* 420:788–794.
- Zuo Y, Lin A, Chang P, Gan WB (2005) Development of long-term dendritic spine stability in diverse regions of cerebral cortex. *Neuron* 46:181–189.
- Zuo Y, Yang G, Kwon E, Gan WB (2005) Long-term sensory deprivation prevents dendritic spine loss in primary somatosensory cortex. *Nature* 436:261–265.
- Purves D, Hadley RD (1985) Changes in the dendritic branching of adult mammalian neurons revealed by repeated imaging *in situ*. *Nature* 315:404–406.
- Hofer SB, Mrsic-Flogel TD, Bonhoeffer T, Hübener M (2009) Experience leaves a lasting structural trace in cortical circuits. *Nature* 457:313–317.
- Holtmaat A, Willbrecht L, Knott GW, Welker E, Svoboda K (2006) Experience-dependent and cell-type-specific spine growth in the neocortex. *Nature* 441:979–983.
- Matsuzaki M, Honkura N, Ellis-Davies GC, Kasai HM (2004) Structural basis of long-term potentiation in single dendritic spines. *Nature* 429:761–766.
- Costa RM, Cohen D, Nicoletti MA (2004) Differential corticostriatal plasticity during fast and slow motor skill learning in mice. *Curr Biol* 14:1124–1134.
- Draganski B, et al. (2004) Changes in gray matter induced by training. *Nature* 427:311–312.
- Mechelli A, et al. (2004) Neurolinguistics: Structural plasticity in the bilingual brain. *Nature* 431:757.
- Carreiras M, et al. (2009) An anatomical signature for literacy. *Nature* 461:983–986.
- Maguire EA, et al. (2000) Navigation-related structural change in the hippocampi of taxi drivers. *Proc Natl Acad Sci USA* 97:4398–4403.
- Aydin K, et al. (2007) Increased gray matter density in the parietal cortex of mathematicians: A voxel-based morphometry study. *AJNR Am J Neuroradiol* 28: 1859–1864.
- Lee H, et al. (2007) Anatomical traces of vocabulary acquisition in the adolescent brain. *J Neurosci* 27:1184–1189.
- Kay P, Regier T (2003) Resolving the question of color naming universals. *Proc Natl Acad Sci USA* 100:9085–9089.
- Regier T, Kay P, Cook RS (2005) Focal colors are universal after all. *Proc Natl Acad Sci USA* 102:8386–8391.
- Markson L, Bloom P (1997) Evidence against a dedicated system for word learning in children. *Nature* 385:813–815.
- Zhou K, et al. (2010) Newly trained lexical categories produce lateralized categorical perception of color. *Proc Natl Acad Sci USA* 107:9974–9978.
- Ashburner J, Friston KJ (2000) Voxel-based morphometry—the methods. *Neuroimage* 11:805–821.
- Hoefel F, et al. (2007) Functional and morphometric brain dissociation between dyslexia and reading ability. *Proc Natl Acad Sci USA* 104:4234–4239.
- Siok WT, Niu Z, Jin Z, Perfetti CA, Tan LH (2008) A structural-functional basis for dyslexia in the cortex of Chinese readers. *Proc Natl Acad Sci USA* 105:5561–5566.
- Tan LH, et al. (2008) Language affects patterns of brain activation associated with perceptual decision. *Proc Natl Acad Sci USA* 105:4004–4009.
- Siok WT, et al. (2009) Language regions of brain are operative in color perception. *Proc Natl Acad Sci USA* 106:8140–8145.
- Zeki S, et al. (1991) A direct demonstration of functional specialization in human visual cortex. *J Neurosci* 11:641–649.
- Wandell BA (1999) Computational neuroimaging of human visual cortex. *Annu Rev Neurosci* 22:145–173.
- Bartels A, Zeki S (2004) Functional brain mapping during free viewing of natural scenes. *Hum Brain Mapp* 21:75–85.
- Ziv NE, Ahissar E (2009) Neuroscience: New tricks and old spines. *Nature* 462: 859–861.
- Gilbert AL, Regier T, Kay P, Ivry RB (2006) Whorf hypothesis is supported in the right visual field but not the left. *Proc Natl Acad Sci USA* 103:489–494.
- Reber PJ, Stark CEL, Squire LR (1998) Cortical areas supporting category learning identified using functional MRI. *Proc Natl Acad Sci USA* 95:747–750.
- Quallo MM, et al. (2009) Gray and white matter changes associated with tool-use learning in macaque monkeys. *Proc Natl Acad Sci USA* 106:18379–18384.
- Kay P, Kempton W (1984) What is the Sapir-Whorf hypothesis? *Am Anthropol* 86: 65–78.
- Roberson D, Davidoff J, Davies IR, Shapiro LR (2005) Color categories: Evidence for the cultural relativity hypothesis. *Cognit Psychol* 50:378–411.
- Winawer J, et al. (2007) Russian blues reveal effects of language on color discrimination. *Proc Natl Acad Sci USA* 104:7780–7785.
- Roberson D, Hanley JR (2007) Color vision: color categories vary with language after all. *Curr Biol* 17:R605–R607.
- Drivonikou GV, et al. (2007) Further evidence that Whorfian effects are stronger in the right visual field than the left. *Proc Natl Acad Sci USA* 104:1097–1102.
- Franklin A, et al. (2008) Categorical perception of color is lateralized to the right hemisphere in infants, but to the left hemisphere in adults. *Proc Natl Acad Sci USA* 105:3221–3225.
- Franklin A, et al. (2008) Lateralization of categorical perception of color changes with color term acquisition. *Proc Natl Acad Sci USA* 105:18221–18225.
- Roberson D, Pak H, Hanley JR (2008) Categorical perception of colour in the left and right visual field is verbally mediated: Evidence from Korean. *Cognition* 107:752–762.
- Özgen E, Davies IRL (2002) Acquisition of categorical color perception: A perceptual learning approach to the linguistic relativity hypothesis. *J Exp Psychol Gen* 131:477–493.
- Ashburner J, Friston KJ (2005) Unified segmentation. *Neuroimage* 26:839–851.
- Talairach J, Tournoux P (1988) Co-planar stereotaxic atlas of the human brain. (Theime Medical, New York).