Whorf hypothesis is supported in the right visual field but not the left

Aubrey L. Gilbert*[†][‡], Terry Regier[§], Paul Kay[¶][‖], and Richard B. Ivry***

*Helen Wills Neuroscience Institute and Departments of [†]Psychology and [‖]Linguistics, University of California, Berkeley, CA 94720; [§]Department of Psychology, University of Chicago, Chicago, IL 60637; and [¶]International Computer Science Institute, 1947 Center Street, Berkeley, CA 94704

Contributed by Paul Kay, November 16, 2005

The question of whether language affects perception has been debated largely on the basis of cross-language data, without considering the functional organization of the brain. The nature of this neural organization predicts that, if language affects perception, it should do so more in the right visual field than in the left visual field, an idea unexamined in the debate. Here, we find support for this proposal in lateralized color discrimination tasks. Reaction times to targets in the right visual field were faster when the target and distractor colors had different names; in contrast, reaction times to targets in the left visual field were not affected by the names of the target and distractor colors. Moreover, this pattern was disrupted when participants performed a secondary task that engaged verbal working memory but not a task making comparable demands on spatial working memory. It appears that people view the right (but not the left) half of their visual world through the lens of their native language, providing an unexpected resolution to the language-and-thought debate.

categorical perception | color | hemispheric laterality | linguistic relativity

Does the language we speak affect our perception of the world (1, 2)?[††] This classic question continues to provoke controversy (3–5). Even in the thoroughly investigated domain of color, some studies suggest that language may affect color perception (6–8), although others suggest that it does not (9–12). However, this question has not been addressed in terms of the functional organization of the brain, which suggests a possible resolution. Specifically, consideration of brain organization predicts that language may affect perception in the right half of the visual field but not in the left half, consistent with both views at once.

Speakers of English judge colors that straddle the English category boundary between "green" and "blue" to be less similar than speakers of Tarahumara, a Uto-Aztecan language of Mexico that, like the majority of the world's languages, uses a single word for these colors (6). Such categorical perception of color is eliminated under conditions designed to interfere with verbal processing (6–8). These results suggest that language may affect perceptual discrimination through the spontaneous but unspoken use of lexical codes. If so, these lexical codes are likely to be more strongly represented in the left hemisphere (LH) of the brain because a preferential involvement of the LH is observed for almost all language tasks (13, 14), including those requiring lexical access (15).

Given the contralateral nature of visual projections to the cortex, information from the right visual field (RVF) would, at least initially, have preferential access to, and be more susceptible to modulation by, lexical representations in the LH. This fact suggests that an effect of language on perceptual discrimination would be seen primarily for stimuli in the RVF. Although some earlier findings (16–19) are compatible with this proposal, to our knowledge it has not been directly tested. We do so here.

We test three predictions based on the hypothesis that language will disproportionately influence color discrimination in the RVF as compared with the left visual field (LVF). First, discrimination between colors from different lexical categories (i.e., that have different names) should be faster when stimuli are displayed in the RVF than when they are displayed in the LVF because the lexical distinction will enhance the perceptual difference. Second, discrimination between colors from the same lexical category should be slower in the RVF than in the LVF, because the assignment of the same name to two colors will diminish the perceptual difference. Third, these laterality effects should be disrupted when language resources are taxed by the demands of an interference task.

Experiment 1, Results, and Discussion

We used a visual search task to test the predictions outlined above. The search involved colors drawn from a set of four, which we designated A, B, C, and D. These four colors form a graded series from green to blue, the green–blue boundary falling between B and C (Fig. 1*a*). In the visual search task, each stimulus display consisted of a ring of colored squares surrounding a central fixation marker. All of the squares were of the same color except for one, the target (Fig. 1*b*). The target and distractor colors were either from within the same lexical category (e.g., different shades of blue) or from different lexical categories (e.g., a green and a blue). On each trial, participants were asked to indicate whether the target was in the left or right half of the circle, by making speeded keyboard responses with the corresponding hand. In this manner, we manipulated two variables: the visual field of the target and the categorical relationship between the target and distractor colors. This visual search task was performed with or without a concurrent verbal-interference task, which consisted of silently rehearsing an eight-digit number throughout a block of visual search trials and recalling it at the end of the block. There were four types of target–distractor pairs: 1-step within-category (AB and CD), 1-step between-category (BC), 2-step between-category (AC and BD), and 3-step between-category (AD).

Trials in which the participant pressed the wrong key or any nondesignated key or in which the reaction time (RT) was >2 SD from the participant's mean were not included in the analysis of the visual search data. About 8% of all trials were excluded by the criteria just mentioned, 75% of these because of erroneous responses. There was an approximately equal distribution of excluded trials between the two visual fields, and error rates were similar for within- and between-category trials. On ≈89% of the blocks with verbal interference, participants entered the correct eight-digit number; on the remaining blocks, errors were typi-

---

Conflict of interest statement: No conflicts declared.

Abbreviations: LH, left hemisphere; LVF, left visual field; RT, reaction time; RVF, right visual field.

[‡] To whom correspondence may be addressed at: Helen Wills Neuroscience Institute and Department of Psychology, 3210 Tolman Hall #1650, University of California, Berkeley, CA 94720-1650. E-mail: mayfly@berkeley.edu.

** To whom correspondence may be addressed. E-mail: kay@icsi.berkeley.edu.

[††] We use the term "perception" throughout this paper in the broad sense in which it is commonly employed in the language-and-thought literature; however, a more restricted concept of perception is also examined in *General Discussion*.

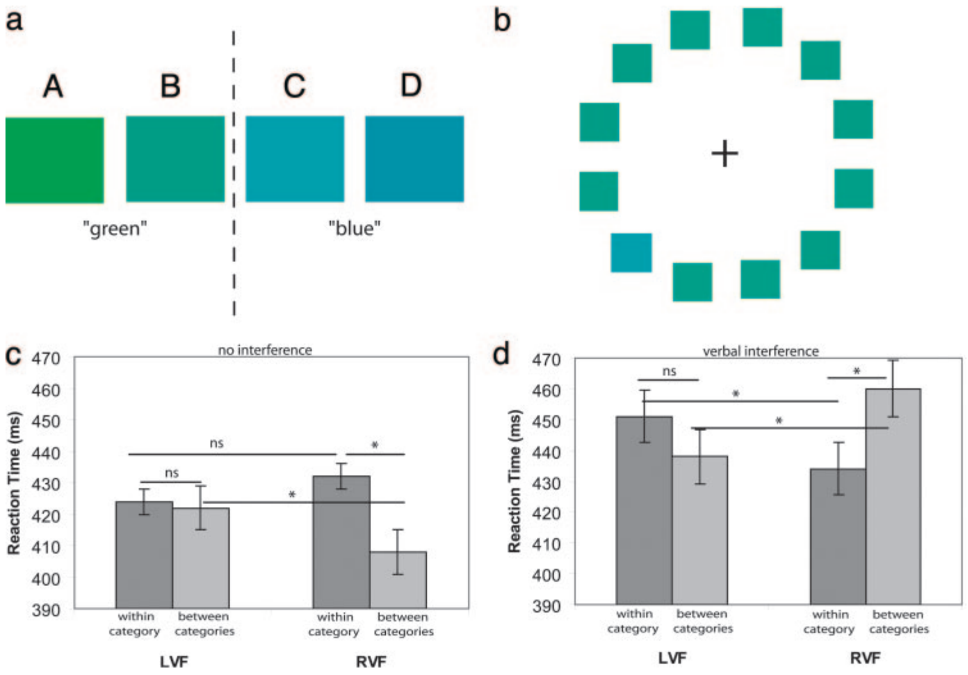

Fig. 1. Lexical categories influence perception in the RVF. (*a*) Print-rendered versions of the four colors used. (*b*) Sample display for the visual search task. Participants were required to press one of two response keys, indicating the side containing the target color. (*c*) In the no-interference condition, RTs were faster for the between-category pair and slower for the within-category pairs when targets appeared in the RVF compared with when they appeared in the LVF. (*d*) Effects were reversed with verbal interference. *, $P < 0.05$, two-tailed *t* test, $df = 10$; ns, nonsignificant. Values are mean ± SEM.

cally of the form that participants either failed to report one digit or inverted the order of two digits.

Not surprisingly, there was a significant effect of step size: targets were detected more quickly when they were less similar to distractors [$F_{(2,10)} = 12.36, P < 0.01$]. The mean RTs for the 3-step, 2-step, and 1-step pairs, respectively, were 402 ms, 407 ms, and 422 ms in the no-interference condition and 428 ms, 433 ms, and 444 ms in the interference condition (collapsed over within- and between-category pairs). This observation confirms that RT in the visual search task is sensitive to the discriminability of the stimuli.

We focus on the 1-step pairs, because it is only at this step size that both within- and between-category pairs exist. The RT data from the no-interference condition were analyzed by using a 2 (visual field: left vs. right) × 2 (pair type: within- vs. between-category) ANOVA (Fig. 1*c*). There was a reliable main effect of pair type, with between-category pairs faster than within-category pairs [$F_{(1,10)} = 8.43, P < 0.02$]. There was no effect of visual field [$F_{(1,10)} = 1.57, P = 0.24$]. The interaction was significant [$F_{(1,10)} = 16.11, P < 0.01$], indicating faster between-category discrimination in the RVF.

For the between-category pair, RTs were faster by 14 ms when the target appeared in the RVF than when it appeared in the LVF ($t = 2.23, P < 0.05$). The opposite pattern approached significance for the within-category pairs: RTs were faster by 8 ms when the target appeared in the LVF than when it appeared in the RVF ($t = 1.84, P = 0.09$).

We also compared RTs for within-category vs. between-category pairs within each visual field. For RVF targets, participants' responses to the between-category pair were 24 ms faster than to within-category pairs ($t = 2.78, P < 0.02$). For LVF targets, RTs were similar for within- and between-category pairs ($t = 0.19, P = 0.85$). Thus, color names influenced RVF responses but not LVF responses.

We performed a similar ANOVA on the data from the verbal-interference condition (Fig. 1*d*). The effect of pair type was significant [$F_{(1,10)} = 6.75, P < 0.05$], but the effect of visual field was not [$F_{(1,10)} = 2.89, P = 0.12$]. The interaction was again significant [$F_{(1,10)} = 26.27, P < 0.01$], but the pattern of results was quite different from that observed without interference. Although we had expected that the RVF advantage for the between-category pair would be attenuated when the search task was performed concurrently with the verbal-interference task, we found that RTs on these trials were actually 22 ms faster when the target appeared in the LVF ($t = 2.79, P < 0.02$). Similarly, RTs for within-category pairs were now 17 ms faster when the target appeared in the RVF ($t = 2.31, P < 0.05$).

Considering the data by visual field for RVF targets, RTs were now 26 ms slower for the between-category pair than for within-category pairs ($t = 2.33, P < 0.05$). The opposite pattern approached significance for the LVF: RTs were faster by 13 ms for the between-category pair than for the within-category pairs ($t = 2.05, P = 0.07$). Thus, the addition of the verbal-interference task reversed the visual field asymmetries observed when the visual search task was performed alone.

Finally, we performed a three-way ANOVA (visual field × pair type × secondary task: no interference vs. verbal interference) directly to compare the no-interference and interference conditions. As expected, there was a main effect of secondary task, with slower RTs when the participants were concurrently engaged in the verbal-interference task [$F_{(1,10)} = 6.12, P < 0.05$]. Most importantly, the three-way interaction (secondary task: none vs. verbal × visual field × pair type) was reliable [$F_{(2,10)} = 16.37, P < 0.01$]. Consistent with the results reported above, the secondary task × pair type interaction was only reliable when targets appeared in the RVF [$F_{(1,10)} = 27.21, P < 0.01$] and not when they appeared in the LVF [$F_{(1,10)} = 2.74, P = 0.13$].

The results of experiment 1 are consistent with the hypothesis that linguistic categories selectively influence color discrimination in the RVF. Color names modulated color discrimination, enhancing between-category distinctions and perhaps reducing

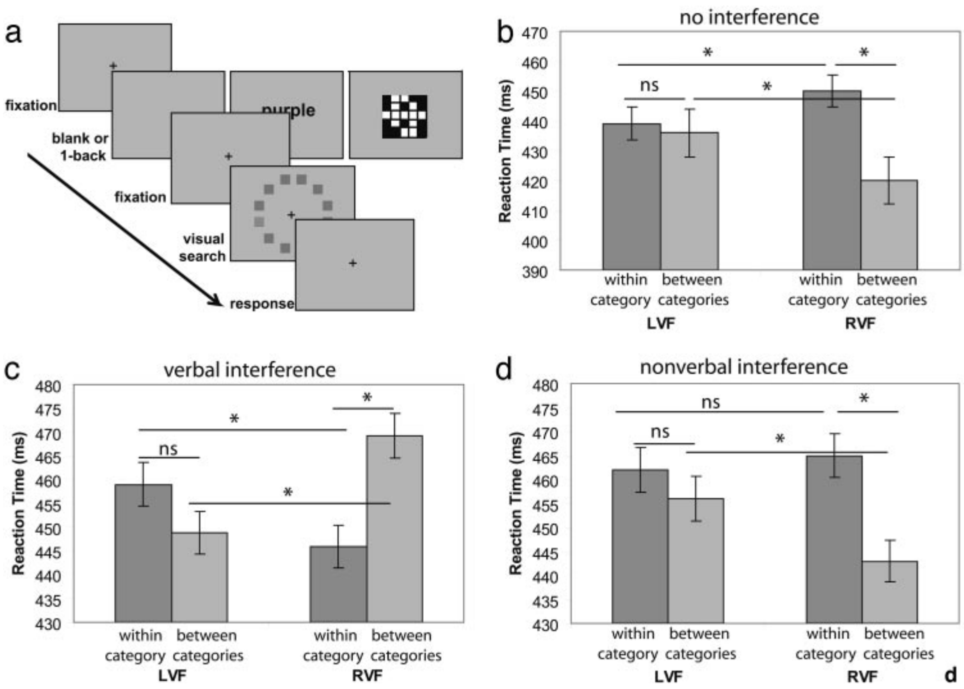

Fig. 2. Modulation of color-category effects in the RVF is specific to linguistic demands of the interference task. (*a*) Trial events. Within a block of trials, the visual search task was interleaved with blank displays, displays containing a color word, or displays containing a spatial grid. (*b* and *c*) No-interference and verbal-interference results replicate those obtained in the first experiment. (*d*) For the nonverbal-interference condition, performance followed a pattern similar to that observed in the no-interference condition. *, $P < 0.05$, two-tailed *t* test, $df = 10$; ns, nonsignificant.

within-category distinctions, but only when the target appeared in the RVF. These effects were disrupted by verbal interference.

Experiment 2, Results, and Discussion

We have assumed that the disruption caused by the interference task was related to its specifically verbal processing requirements. However, it is important to verify this point (7, 8). To this end, we conducted a second experiment, similar to the first, but employing both verbal and nonverbal concurrent interference tasks. In the verbal-interference task, participants were shown a word for a color (e.g., "red") before each visual search trial. They had to remember the word during the visual search; upon seeing the color term at the beginning of the next trial, they were to respond if it matched the one they had seen previously (one-back match). In the nonverbal-interference task, participants had to remember a spatial grid of squares instead (Fig. 2*a*). We expected that the influence of language on color discrimination in the RVF would be disrupted by the verbal-interference task but not by the nonverbal-interference task.

Trials were excluded from the RT analysis by using the same criteria as in experiment 1. The mean number of excluded trials was 6%, 8%, and 9% for no-interference, verbal-interference, and nonverbal-interference conditions, respectively, with almost all of these exclusions due to trials in which the wrong key was pressed. Errors were approximately equal for RVF targets and LVF targets.

In the verbal-interference task, participants responded correctly on 91% of the trials for which the interference display matched the previous one; this proportion was 89% in the nonverbal-interference condition. In addition, there were a small number of false alarms. In analyses of the visual search data, we excluded trials occurring after any responses to these secondary tasks.

As in experiment 1, RT was inversely related to step size [$F_{(1,10)} = 10.07$, $P < 0.01$]. The mean RTs for the 2-step and 1-step pairs, respectively, were 415 ms and 436 ms in the no-interference condition, 430 ms and 456 ms in the verbal-interference condition, and 433 ms and 456 ms in the nonverbal-interference condition (collapsed over within- and between-category pairs; the 3-step pair AD was not tested in experiment 2).

Focusing again on the 1-step pairs, the results for the no-interference and verbal-interference conditions replicated the results for the corresponding conditions in experiment 1 (Fig. 2 *b* and *c*). Initial analyses with 2 (visual field) × 2 (pair type) ANOVAs for the no-interference and verbal-interference conditions again demonstrated reliable main effects of pair type [no interference, between-category faster: $F_{(1,10)} = 9.95$, $P < 0.01$; verbal interference, within-category faster: $F_{(1,10)} = 5.87$, $P < 0.05$]. The effect of visual field approached significance for both conditions [no interference: $F_{(1,10)} = 3.38$, $P = 0.10$; verbal interference: $F_{(1,10)} = 3.72$, $P = 0.08$].

The visual field by pair type interaction was significant in both of these conditions, [no interference: $F_{(1,10)} = 12.60$, $P < 0.01$; verbal interference: $F_{(1,10)} = 23.46$, $P < 0.01$]. In the no-interference condition, between-category RTs were faster by 16 ms when the target appeared in the RVF than when it appeared in the LVF ($t = 2.46$, $P < 0.05$). The opposite pattern was observed for the within-category pairs: RTs were faster by 11 ms when the target appeared in the LVF than when it appeared in the RVF ($t = 2.27$, $P < 0.05$). Similar to our analysis for experiment 1, we also compared RTs within each visual field separately. When targets appeared in the RVF, participants' responses were faster by 30 ms for the between-category pair than for the within-category pairs ($t = 2.93$, $P < 0.02$). In contrast, when targets appeared in the LVF, RTs for the within-category pairs were not significantly different from those for the between-category pair ($t = 0.05$, $P = 0.96$).

As in experiment 1, this pattern was reversed when the participants were required to perform a concurrent verbal-interference task. For the between-category pair, RTs were 20 ms faster when the target appeared in the LVF than in the RVF ($t = 2.68$, $P < 0.05$). The RTs for within-category pairs were 13 ms faster when the target appeared in the RVF than when it appeared in the LVF ($t = 2.56, P < 0.05$). For the within-visual field analyses for RVF targets, RTs were 23 ms slower for the between-category pair than for within-category pairs ($t = 2.75$, $P < 0.05$). The opposite pattern approached significance in the LVF: RTs were 10 ms slower for within-category pairs than for between-category pairs ($t = 1.88, P = 0.09$).

As expected, the results for the nonverbal-interference condition were similar to those observed in the no-interference condition but with generally slower RTs. (Fig. 2*d*). The main effect of pair type was significant [$F_{(1,10)} = 5.66, P < 0.05$], but the effect of visual field was not [$F_{(1,10)} = 2.55, P = 0.14$], and these factors interacted [$F_{(1,10)} = 7.50, P < 0.05$]. These results did not resemble those of the verbal-interference condition. For the between-category pair, RTs were 13 ms faster when targets appeared in the RVF than when they appeared in the LVF ($t = 2.32, P < 0.05$). For within-category pairs, RTs did not differ significantly for targets appearing in the RVF and LVF ($t = 0.26$, $P = 0.80$). In the within-visual-field analyses, RVF RTs were 22 ms faster for the between-category pair than for within-category pairs ($t = 2.75, P < 0.05$). This pattern did not reach significance in the LVF ($t = 1.65, P = 0.13$).

To compare the verbal- and nonverbal-interference conditions directly, we performed a three-way ANOVA. This analysis revealed a significant three-way interaction between visual field, pair type, and secondary task (by using just two factors, verbal and nonverbal) [$F_{(2,20)} = 12.53, P < 0.01$]. As can be seen in Fig. 2, the two interference tasks had different effects for targets presented in the RVF, with only the verbal-interference task reversing the between-category advantage. In contrast, the two interference tasks had similar effects for targets in the LVF.

Taken together, these results are consistent with the hypothesis that language modulates color discrimination in the RVF by means of lexical categories, whereas it has little, if any, effect on the discrimination of color in the LVF. Moreover, this pattern is disrupted by verbal, but not by nonverbal, interference.

Experiment 3, Results, and Discussion

The logic of experiments 1 and 2 rests on the assumption that targets in the RVF will be primarily represented in the LH. Although a large body of studies with neurologically intact individuals supports this assumption (14), lateralized inputs can readily become available to both hemispheres, primarily through interhemispheric communication across the corpus callosum. Callosotomy patients provide a less inferential method to bias processing to a single hemisphere and thus can provide converging evidence that language selectively modulates representations in the LH/RVF. We tested one such individual, JW, on a version of the visual search task. JW underwent a two-stage callosotomy operation in 1979–1980 for intractable epilepsy (20). The linguistic competence of each hemisphere in this individual has been extensively documented, and, despite slight improvement in right hemisphere linguistic competence when tested 15 years after surgery, JW has remained consistently left hemisphere language dominant (21). JW has suffered two strokes over the past two years, resulting in LH lesions primarily in the parietal lobe. Chronic deficits related to the stroke include a right-sided somatosensory deficit and reduced dexterity of the right hand. There is no clinically observable neglect or aphasia, and JW had little difficulty understanding and performing the tasks.

Only 5% of the trials were excluded by using the criteria described in experiment 1. Of these excluded trials, 45% involved erroneous responses, 20% involved trials in which a nondesignated key was pressed, and the remainder had RTs beyond 2 SD from the mean. Slightly more exclusions due to a nondesignated key being pressed occurred with the right hand (62%), likely because of JW's coordination problems related to previous strokes, and more exclusions based on the RT criteria were imposed for left-hand responses (68%) than right-hand responses. The erroneous responses were distributed equally for RVF and LVF targets. Similar to the results of the first two experiments, JW was faster at responding on trials with 2-step pairs than on those with 1-step pairs [$F_{(1,\ 10)} = 10.2, P < 0.01$]. The mean RTs for the 2- and 1-step pairs were 434 ms and 487 ms, respectively. The 3-step pair, AD, was not tested in this experiment.

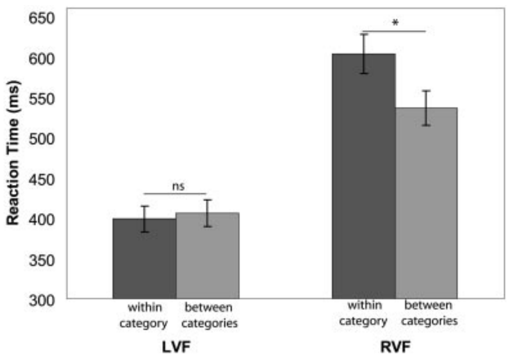

Fig. 3. Lexical categories influence perception in the RVF of a callosotomy patient. $*$, $P < 0.05$, two-tailed *t* test, $df = 1$; ns, nonsignificant.

For the 1-step pairs (Fig. 3), we observed reliable main effects of visual field [$F_{(1,7)} = 22.46, P < 0.01$] and pair type [$F_{(1,7)} = 7.98, P < 0.05$], as well as an interaction of these variables [$F_{(1,\ 10)} = 17.91, P < 0.01$]. JW was considerably slower in responding to targets in the RVF, consistent with his right-hand apraxia and somatosensory deficits related to the strokes. Nonetheless, RVF responses for the between-category pair were still 67 ms faster than for the within-category pairs ($t = 14.3, P < 0.05$). For targets in the LVF, RTs did not differ for the between- and within-category pairs ($t = 1.01, P = 0.50$). Another way to consider the interaction is to observe that the RVF RT cost was 204 ms for the within-category pairs but only 130 ms for the between-category pair. Thus, although the callosotomy patient is much slower to respond to RVF targets in general, the cost is significantly reduced when the target and distractor can be lexically differentiated.

General Discussion

The results of these three experiments establish that, for the visual search task used here, the Whorf hypothesis is supported most strongly, even exclusively, in the RVF. Experiment 1 showed that color names influence color discrimination in the RVF but not the LVF. Discrimination of colors with different names is faster in the RVF than in the LVF. This experiment also established that this laterality effect was attenuated and even reversed when verbal working memory was taxed by a concurrent interference task. Experiment 2 replicated these results, showing that discrimination of colors in the same category was slower in the RVF than in the LVF, and that a concurrent interference task that taxed spatial working memory did not disrupt the laterality effect. Converging evidence that the laterality effect was related to hemispheric asymmetries was obtained in experiment 3; here, a split-brain patient was shown to have an RVF advantage for between-category discrimination over within-category discrimination.

Whorf referred to the effects of language in terms of how it is used to "cut nature up" (ref. 1, p. 213) without clearly delineating the distinction between perception and other aspects of cognition, such as decision making. When we use the term "perception," we intend it in the same broad sense. We employ the expressions "perceptual discrimination" and "discrimination" specifically to describe our participants' behavior on the visual search task.

There are at least two reasons that color discrimination might be affected by language in our findings, as in the literature more generally. One possibility is that language affects perception directly; by this view, language alters the nature of the early visual response to colors, with this effect especially pronounced in the left hemisphere. Another possibility is that language facilitates postperceptual processes (22, 23). On this view, the effect of language on the decision process is much stronger in the left hemisphere, leading to the categorical effects observed in performance. It is, of course, also possible that there is some truth in both hypotheses. Our results do not discriminate among these possibilities.[‡‡] However, whether language affects perception, postperceptual processes, or both, any influence of language on perceptual discrimination clearly falls within the broad formulation of Whorf's hypothesis.

Previous studies addressing the possible influence of language on perception have tended to look for a simple yes or no answer to the question. Our findings suggest a more complex picture, based on the functional organization of the brain. The LH appears to sharpen visual distinctions between lexically defined categories and to blur visual distinctions within these categories, whereas the right hemisphere does so much less, if at all. To the degree that these results can be generalized to everyday perception, our representation of the visual world may be, at one and the same time, filtered and not filtered through the categories of language.

Materials and Methods

Experiment 1. ***Participants.*** Thirteen participants were recruited from the University of California, Berkeley, community. The participants (mean age = 20 years) were right-handed, native English speakers, and, based on self-reports, had normal color vision.

Equipment and stimuli. The stimuli A, B, C, and D (Munsell 7.5G, 2.5BG, 7.5BG, and 2.5B) were used in a previous study (6); we used computer-generated versions of them. The color calibration wizard at www.easyrgb.com was used to standardize the computer monitor. The red–green–blue (RGB) values were identified by using a searchable database, also at www.easyrgb.com. The brightness and saturation values were adjusted to make them equal, based on the independent judgments of four observers. The 8-bit RGB values were as follows: A = 0, 171, and 129; B = 0, 170, and 149; C = 0, 170, and 170; and D = 0, 149, and 170.[§§] The RGB values for the background were 178, 178, and 178.

Procedure. First, each participant's blue–green lexical boundary was determined. In each trial of this preliminary task, a square stimulus (one of the colors, A, B, C, or D) was presented centrally on a neutral gray screen for 200 ms. Participants labeled the stimulus either green or blue by pressing the "G" or "B" keys on the computer keyboard. Each stimulus was presented 10 times in a total of 40 randomized trials. The lexical boundary was defined as the point of subjective equality (i.e., the estimated value where green would be reported half of the time). Only the 11 participants who placed the blue–green boundary between stimuli B and C were included in analysis of the visual search data.

The visual search itself was then conducted. Each trial began with the onset of a central fixation marker. After 1,000 ms, the stimulus display appeared, consisting of a ring of 12 squares surrounding the fixation marker. Responses were made by pressing one of two horizontally aligned keys on the keyboard, by using either the left ("Q" key) or right ("P" key) index finger. The visual search display remained visible until a response was made. After the response, no feedback was provided, and the screen went blank for 250 ms before the fixation marker appeared to indicate the start of the next trial. Although participants were instructed to maintain fixation, we did not monitor eye movements.

There were 12 target–distractor pairs, formed by using all pairwise combinations of the four colors (six pairs) and having each member of a pair serve once as target and once as distractor. Because the target could occupy any of 12 positions, there were 144 possible stimulus configurations. Each participant completed six 144-trial blocks, with each stimulus configuration appearing at random, once per block. For three of the blocks, the visual search task was performed alone; for the other three, the search task was performed with the concurrent verbal-interference task. For the verbal-interference task, the eight digits were randomly selected without replacement from the set of single-digit numbers and were presented before the start of the block of visual search trials. The numbers were presented sequentially, with each digit appearing for 1,000 ms followed by an interdigit interval of 200 ms. After the visual search block, the participant recalled the list, typing in the numbers on the keyboard number pad.

Participants completed three blocks of one condition (visual search alone or concurrent with verbal interference) and then three blocks of the other condition. The order of tasks was counterbalanced across subjects. Before the first block of each task, a short 10-trial practice block was administered.

Experiment 2. ***Participants.*** Thirteen participants were recruited from the University of California, Berkeley, community, using the same criteria as in experiment 1. The mean age of the participants was again 20 years.

Procedure. The lexical boundary determination task was performed as in experiment 1, and again, 11 of the 13 original participants placed the green–blue boundary between stimuli B and C. We again excluded the data of the other two participants from the analysis of the visual search data.

The visual search task was similar to that of experiment 1, with three changes. First, the relatively uninformative 3-step pair (AD) was excluded. Second, for each of the remaining five pairs, only one member, randomly selected, served as the target. These two changes reduced the total number of stimulus displays to 60 (five pairs, with the target appearing in each of the 12 possible locations), a number that allowed us to complete testing with the search task alone as well as with the two interference tasks. Third, the exposure time of the visual search displays was limited to 200 ms, thus rendering eye movements, if present, ineffective in identifying the target.

For the verbal-interference task, the interference display consisted of a single color word drawn from the set: "beige," "black," "brown," "gray," "orange," "pink," "purple," "red," "violet," "white," and "yellow." For the nonverbal-interference task, the displays consisted of a 5-cm × 5-cm grid in which 12 of the 25 squares were black and 13 were white. A set of 15 displays

NEUROSCIENCE

PSYCHOLOGY

[‡‡] Behavioral methods may not prove sufficient to distinguish between these alternatives. Physiological procedures might identify both the location and timing at which the two hemispheres diverge in their response to stimuli such as those used in our color discrimination task (24, 25).

[§§] After the experiment, we determined the coordinates of the color stimuli in the CIEL*a*b* and CIEL*u*v* color spaces by using the conversion software at www.easyrgb.com, with parameters set to illuminant "daylight" and observer "2 degrees." For the CIEL*a*b* space, the interstimulus distances were: AB, 12.3; BC,12.5; and CD, 15.7. For the CIEL*u*v* space, the interstimulus distances were: AB, 16.3; BC, 17.5; and CD, 19.5. In both spaces, the within-green (AB) distance is slightly less than the between-category (BC) distance, and the within-blue differences is larger. In both cases, the average of the within-distances (AB and CD) exceeds the between-distance (BC). Whereas we collapse across the within-category pairs in the analyses reported in the main text, these differences led us to perform secondary analyses in which we treated the data for the within-green and within-blue conditions separately, rather than pooled. In no case did the outcome of these secondary analyses deviate from that reported in the main text.

was created. On no-interference blocks, a blank screen was presented in lieu of an interference display.

The visual search and interference displays were interleaved (Fig. 2*a*). A fixation marker was presented for 1,250 ms. It was then replaced by a blank screen (no interference), a color name (verbal interference), or one of the spatial grids (nonverbal interference) for 1,250 ms. The fixation screen then reappeared for another 1,250 ms, followed by the visual search display for 200 ms. The instructions emphasized that participants should respond as quickly as possible to the visual search displays, by using their left or right index finger to press the "Q" or "P" key on the keyboard to indicate the side of the target. During interference blocks, they were also required to press the space bar with both thumbs whenever they detected that the secondary task stimulus was the same as that shown in the previous display (one-back match). No response was required when the secondary task stimulus changed. Matches occurred in ≈10% of trials. This low percentage was selected because RTs on the visual search task are likely to be inflated when these responses are made shortly after another overt response (26). For this reason, we excluded trials occurring after overt secondary task responses in our analysis of the visual search task data. Extensive pilot testing was conducted to select displays in which accuracy on the nonverbal one-back task was similar to that on the verbal one-back task, when each was performed concurrently with the visual search task.

Each participant completed four 60-trial blocks for each of the three tasks: visual search under no-interference, verbal-interference, and nonverbal-interference conditions. The order of the three tasks was counterbalanced across subjects. A 10-trial practice block preceded the first test block for each condition.

Experiment 3. ***Equipment.*** Testing was conducted at the patient's home, necessitating the use of a laptop computer. As in the previous two experiments, the color calibration wizard at www.easyrgb.com was used to standardize the colors presented on the laptop monitor.

Procedure. JW performed the lexical boundary determination task and visual search tasks (without an interference task). On a first block of 20 trials for the lexical boundary task, the stimuli appeared in the center of the screen for 200 ms. The patient made vocal responses, and these responses were recorded by the experimenter. After this portion of the experiment, a 40-trial block was conducted in which the stimuli were presented for 200 ms in either the LVF or RVF. Again, vocal responses were obtained. For all three presentation locations, JW placed the lexical boundary between stimuli B and C. It is of interest is that the patient was able to vocally label the colors when presented in the LVF, indicating at least some access to lexical codes. However, when the boundary task was repeated before a second session the next day, the patient failed to name stimuli presented in the LVF, always reporting, "I didn't see anything" (although this report almost always came immediately after the stimulus). The change in performance is not uncommon with split-brain patients and likely reflects different states of cortical function due to arousal.

As in experiment 2, the 3-step pair was excluded, resulting in five total pairs. Each member of the pair served both as target and distractor. The 10 pair configurations were each presented six times per block of 60 trials, with target location selected randomly. JW completed eight such 60-trial blocks of the visual search task. Responses were made with the index finger of the left or right hand, to indicate that the target was on the corresponding side of the display. Eye fixation was monitored by the experimenter, who prompted the patient to maintain fixation on the few trials in which movements were detected. Four blocks were tested on each of 2 days and the first block of each session was preceded by 10 practice trials.

We thank Lera Boroditsky for providing counsel; Paul Aparicio for aid with programming pilot studies; Michael Posner, Christian Fiebach, David Presti, and Michael Webster for their comments on the manuscript; and Steven Shevell for suggesting the title. This work was supported by National Science Foundation Grants 0418404 and 0418283 (to P.K. and T.R.) and National Institutes of Health Grant NS40813 (to R.B.I.).

1. Carroll, J. B., ed. (1956) *Language, Thought, and Reality: Selected Writings of Benjamin Lee Whorf* (MIT Press, Cambridge, MA).
2. Gumperz, J. & Levinson, S. C. (1996) *Rethinking Linguistic Relativity* (Cambridge Univ. Press, Cambridge, U.K.).
3. Gordon, P. (2004) *Science* **306,** 496–499.
4. Casasanto, D. (2005) *Science* **307,** 1721–1722.
5. Gordon, P. (2005) *Science* **307,** 1722.
6. Kay, P. & Kempton, W. (1984) *Am. Anthropol.* **86,** 65–79.
7. Roberson, D. & Davidoff, J. (2000) *Mem. Cognit.* **28,** 977–986.
8. Witthoft, N., Winawer, J., Wu, L., Frank, M., Wade, A. & Boroditsky, L. (2003) in *Proceedings of the 25th Annual Meeting of the Cognitive Science Society*, eds. Alterman, R. & Kirsh, D. (Lawrence Erlbaum, Mahwah, NJ), pp. 1247–1252.
9. Heider, E. R. (1972) *J. Exp. Psychol.* **93,** 10–20.
10. Heider, E. R. & Olivier, D. C. (1972) *Cognit. Psychol.* **3,** 337–354.
11. Lindsey, D. T. & Brown, A. M. (2002) *Psychol. Sci.* **13,** 506–512.
12. Franklin, A., Clifford, A., Williamson, E. & Davies, I. (2005) *J. Exp. Child Psychol.* **90,** 114–141.
13. Corballis, M. C. (1991) *The Lopsided Ape: Evolution of the Generative Mind* (Oxford Univ. Press, New York).
14. Hellige, J. B. (1993) *Hemispheric Asymmetry: What's Right and What's Left* (Harvard Univ. Press, Cambridge, MA).
15. Damasio, H., Grabowski, T. J., Tranel, D., Hichwa, R. D. & Damasio, A. R. (1996) *Nature* **380,** 499–505.
16. Davidoff, J. (1976) *Q. J. Exp. Psychol.* **28,** 387–394.
17. Hannay, H. J. (1979) *Brain Lang.* **8,** 191–201.
18. Malone, D. R. & Hannay, H. J. (1978) *Neuropsychologia* **16,** 51–59.
19. Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J. & Gabrieli, J. D. E. (1989) *J. Exp. Psychol. Hum. Percept. Perform.* **15,** 723–735.
20. Sidtis, J. J., Volpe, B. T., Wilson, D. H., Rayport, M. & Gazzaniga, M. S. (1981) *J. Neurosci.* **1,** 323–331.
21. Baynes, K., Wessinger, C. M., Fendrich, R. & Gazzaniga, M. S. (1995) *Neuropsychologia* **33,** 1225–1242.
22. MacLeod, C. M. (1991) *Psychol. Bull.* **109,** 163–203.
23. Pilling, M., Wiggett, A., Özgen, E. & Davies, I. R. L. (2003) *Mem. Cognit.* **31,** 538–551.
24. Raz, A., Fan, J. & Posner, M. I. (2005) *Proc. Natl. Acad. Sci. USA* **102,** 9978–9983.
25. Kosslyn, S. M., Thompson, W. L., Costantini-Ferrando, M. F., Alpert, N. M. & Spiegel, D. (2000) *Am. J. Psychiatry* **157,** 1279–1284.
26. Pashler, H. (1994) *Psychol. Bull.* **116,** 220–244.