

Further evidence that Whorfian effects are stronger in the right visual field than the left

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The Whorf hypothesis holds that differences between languages induce differences in perception and/or cognition in their speakers. Much of the experimental work pursuing this idea has focused on the domain of color and has centered on the issue of whether linguistically coded color categories influence color discrimination. A new perspective has been cast on the debate by recent results that suggest that language influences color discrimination strongly in the right visual field but not in the left visual field (LVF). This asymmetry is likely related to the contralateral projection of visual fields to cerebral hemispheres and the specialization of the left hemisphere for language. The current study presents three independent experiments that replicate and extend these earlier results by using different tasks and testing across different color category boundaries. Our results differ in one respect: although we find that Whorfian effects on color are stronger for stimuli in the right visual field than in the LVF, we find that there are significant category effects in the LVF as well. The origin of the significant category effect in the LVF is considered, and two factors that might account for the pattern of results are proposed.

color categories | hemispheric lateralization | linguistic relativity | visual search

The Whorf hypothesis holds that semantic differences between languages induce differences in perception and/or cognition in their speakers (1). Much of the experimental work pursuing this idea has focused on the domain of color and has centered on the issue of whether linguistically coded color categories influence color discrimination (2–13). A new perspective has been cast on the debate by recent results of Gilbert *et al.* (14), which suggest that language influences color discrimination strongly in the right visual field (RVF) and less so or not at all in the left visual field (LVF). This asymmetry likely is related to the contralateral projection of visual fields to cerebral hemispheres and the specialization of the left hemisphere (LH) for language. It suggests that, within an individual, the Whorf hypothesis may be relevant for processing within one hemisphere and not the other. In consequence, under normal conditions, perceivers may view the world at once filtered through the lens of their language and not so filtered.

In the Gilbert *et al.* study (14), subjects were given a visual search task that required detection of a single target color among 11 identical distractors. The target differed from the distractors in hue, and it was either of a different named category from the distractors (e.g., a blue among greens) or it was from the same category as the distractors (one blue among examples of another blue). The target-distractor perceptual differences for between-category (also known as across-category) discriminations were no greater on average than for within-category discriminations, yet between-category discriminations were significantly faster, but only when the target occurred in the RVF. Because the RVF projects to the LH, which in most people is also the dominant hemisphere for language (15), it was concluded that the implicit use of lexical codes in the LH was probably the origin of the lateralization of what we will refer to as the “category effect”

(faster across- than within-category responses). This interpretation was supported by the finding that a concurrent verbal interference task eliminated the category effect for RVF stimuli, whereas the RVF category effect was preserved with a concurrent spatial interference task.

We present here two bodies of independent corroborating evidence for the lateralized Whorfian effect summarized above. We first describe a reanalysis of color search data from an earlier study by Daoutis *et al.* (16). We then report findings from two new experiments that involve finding a target color against a uniform background. In all three cases, we find that across-category discriminations were made faster than within-category discriminations to a greater degree in the RVF than in the LVF. However, unlike Gilbert *et al.* (14), we do find a significant category effect in the LVF as well, albeit a much weaker one.

Results

Visual Field Effects in a Color Identification Task with Crowded Displays: Reanalysis of Daoutis *et al.* (16). Daoutis *et al.* (16) found that the time to determine whether a specified (i.e., target) color was present in a display of multiple objects was highly influenced by the categorical relationship between that color and distractor colors. Fig. 1*a* depicts the stimuli used: two triplets of colors, three greens (G1, G2, and G3) and a blue, purple pink set (B, Pu, and Pi), in the International Commission on Illumination (CIE) chromaticity diagram ($u'v'$). The $u'v'$ space was designed with the intent that equal distances in the space represent equal perceptual dissimilarities. Thus, the differences within each of the four pairs of adjacent stimuli (G1-G2, G2-G3, B-Pu, and Pu-Pi) are nominally all equal. During training, observers were shown sets of stimuli consisting of a target and distractor colors, with the target consistently identified. After the observers demonstrated that they could remember the target, they were tested on a visual search task, in which a display of 4, 16, or 36 stimuli was shown (Fig. 1*b*). The observer indicated as quickly as possible whether the target was present, with the target, in fact, present on only half of the trials.

Search speed is faster as the dissimilarity between target and distractors increases (17), and, for visual search tasks involving colored targets, search speed is influenced by the relative locations of the stimuli in color space (17). If the three stimuli are colinear (e.g., G1 G2 G3), searching for the middle stimulus is hard (G2 among G1s and G3s), but searching for either of the

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Abbreviations: CIE, Commission Internationale de l'Éclairage (International Commission on Illumination); LH, left hemisphere; LVF, left visual field; RT, reaction time; RVF, right visual field.

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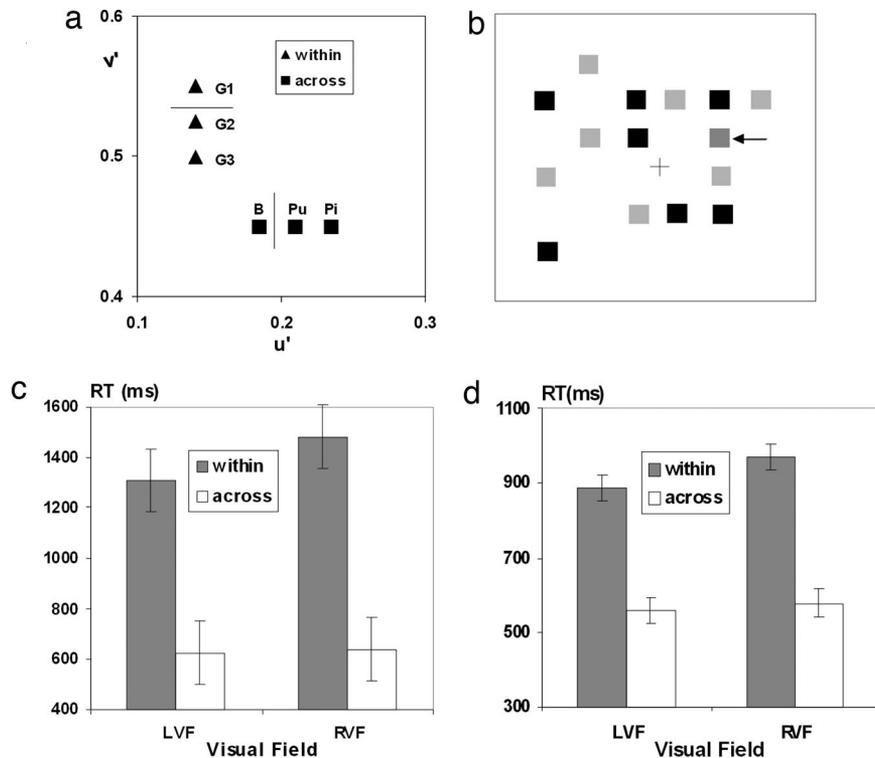


Fig. 1. The category effect is larger in the RVF than in the LVF in a reanalysis of the data from a color identification task used by Daoutis *et al.* (16). (a) Stimuli in CIE coordinates. The within-category set contains three hues of green: G1, G2, G3; the across-category set contains a blue (B), a purple (Pu), and a pink (Pi). Perceptual distance is the same for all adjacent pairs across both sets (G1-G2, G2-G3, B-Pu, and Pu-Pi). When a peripheral stimulus (e.g., G1) is the target, it is linearly separable from the distractors (G2-G3). (b) Illustration of a target-present trial with 15 distractors. The target is indicated here by the arrow that, however, was not present in the display itself. (c and d) Target detection times for within- and across-category targets by LVF and RVF: collapsed across linear separability (c) and linearly separable targets alone (d). Error bars show 95% confidence limits.

outside stimuli is easy (e.g., G1 among G2s and G3s). As a general rule, if the target can be separated from the distractors by a single straight line (G1|G2 G3 and B|Pu Pi in Fig. 1a) the target is “linearly separable” and the search is easy. If they are not, they are “linearly nonseparable” and the search is slow. The aim of the original Daoutis *et al.* study (16) was to see whether categorical separation of the three colors might mitigate this linear nonseparability effect. Experiment 1 compared search performance on the blue-purple-pink set with performance on the green set. For the green set, search for the middle color (G2) took more than twice as long as search for either of the peripheral colors (G1 or G3), whereas, for the categorically separate set, search for the middle color (purple) was no slower than the search for either blue or pink. This large attenuation of the effect of nonseparability also was found in a second experiment comparing a green-blue-purple set with a set of three blues equally separated in hue.

In these experiments, the target, when present, could occur in one of 32 locations. In the original analysis, the data were averaged across target locations. In the present reanalysis, we have considered trials only where the target was present and averaged separately across the 16 target locations to the left of the fixation point and the 16 target locations to the right of the fixation point. Four-factors repeated measure ANOVAs on linear separability (separable/nonseparable), category (within- or across-category), visual field (LVF/RVF), and number of distractors (4, 16, or 36) were performed on the experiment 1 and experiment 2 data. As in the original analysis, there were highly significant effects of linear separability, category, and their interaction for both experiments. Here, we only report statistics pertinent to the visual field effect.

Because the two experiments produced essentially the same

pattern of results, we focus on the reanalysis of the data from experiment 1 of Daoutis *et al.* (16). As Fig. 1c shows, overall target detection in the LVF was ≈ 100 ms faster than in the RVF (1,018 ms as compared with 1,127 ms; $F(1, 7) = 17.71$; $P < 0.005$). This difference was largely due to the within-category condition, in which reaction time (RT) to targets was ≈ 200 ms slower in the RVF than in the LVF. Reaction times to targets in the two visual fields were more or less equal for the across-category case. Importantly, there was a significant interaction between visual field (LVF/RVF) and category (within- or across-category) [$F(1, 7) = 11.92$; $P < 0.01$], with a stronger category effect in the RVF than in the LVF. Put another way, the difference between the within- and across-category conditions was almost 200 ms larger for RVF targets than for LVF targets [$t(7) = 3.49$; $P < 0.01$], consistent with the lateralized Whorf effect observed in ref. 14.

Response times are much slower and the category effects are larger than those reported by Gilbert *et al.* (14). This may reflect the large impact of linear nonseparability on search times and the category effect. The category effect was larger for the nonseparable condition compared with the separable condition (≈ 300 ms compared with ≈ 60 ms) and the category \times field \times separability interaction approached significance [$F(1, 7) = 4.72$; $P = 0.07$]. However, a secondary analysis of just the separable condition showed that the lateralization effect was not restricted to the nonseparable condition (Fig. 1d). The category \times visual field interaction was again significant [$F(1, 7) = 5.57$; $P < 0.05$]; the category effect RT advantage was ≈ 60 ms larger for RVF targets than LVF targets [$t(7) = 2.49$; $P < 0.05$] and seven of eight observers showed this pattern. These response times and category effect are still larger than those reported by Gilbert *et al.*

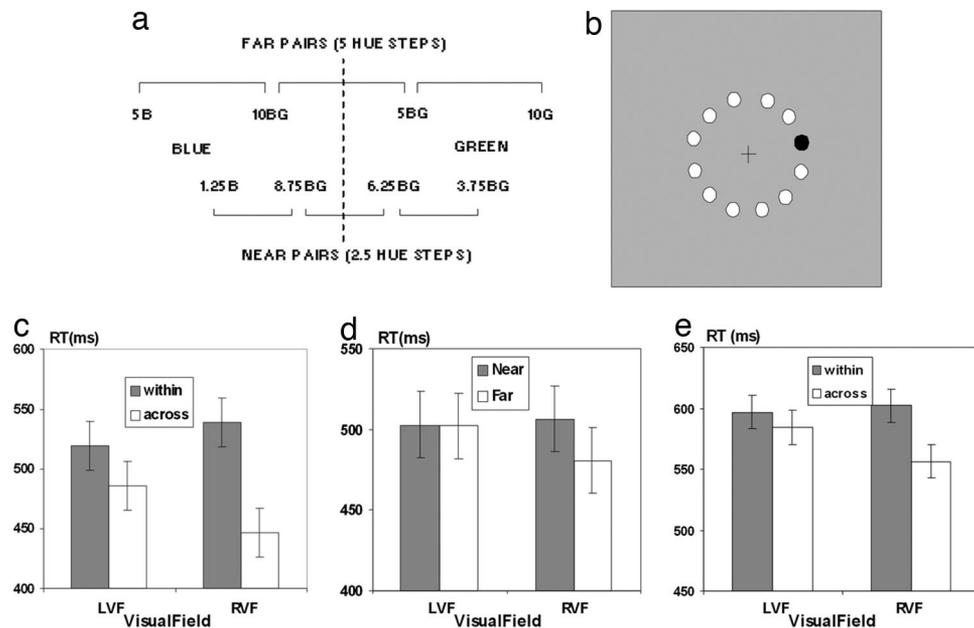


Fig. 2. A larger category effect is observed in the RVF on a color detection task. (a) Munsell codes of the stimuli; stimuli varied in hue at constant value and chroma. Hue separations were either five steps (far set) or 2.5 steps (near set). The target was either in the same color category as the background (e.g., 10BG on 5B, both blue) or in the adjacent category (e.g., 10BG on 5BG, blue on green). (b) Illustration of a test frame: white circles show possible target locations around the fixation cross, and the black circle representing the target. (c and d) Blue-green set: The difference in RT between within- and across-category is larger in the RVF. (e) Blue-purple set: Again, the difference in RT between within- and across-category is larger in the RVF. Error bars are 95% confidence limits.

(14), but much less so than with separable and nonseparable conditions pooled.

A similar pattern was observed in the reanalysis of experiment 2. Detection times in the LVF were ≈ 60 ms faster than those in the RVF [$F(1, 11) = 12.36$; $P < 0.005$], and the interaction between visual field and category was again significant [$F(1, 11) = 6.98$; $P < 0.025$], reflecting the larger category effect in the RVF than in the LVF [$t(11) = 2.64$; $P < 0.025$]. The size of the category effect in the nonseparable condition (≈ 140 ms) was again larger than for the separable condition (≈ 30 ms), but the category effect was still larger in the RVF than the LVF for the separable condition alone [$F(1, 11) = 5.57$; $P < 0.05$].

In both of these experiments, there is a stronger category effect for targets in the RVF than for targets in the LVF. The gain is mostly due to the relative slowness of detecting within-category targets in the RVF, given that across-category target detection took about the same time in both fields. It is noteworthy that, although the difference between the within- and across-category RTs was greater for the RVF, category effects were present in both visual fields. This observation differs from that reported in Gilbert *et al.* (14). In that study, the category effect was restricted to the RVF. The time required to detect within- or across-category targets was comparable in the LVF, but an RT advantage was present on across-category trials in the RVF (see figures 1c and 2b in Gilbert *et al.*; ref. 16).

The differences between the Daoutis *et al.* (16) and the Gilbert *et al.* (14) results may stem from differences in the corresponding tasks. The Daoutis *et al.* (16) observers first had to commit a color to memory and then search a display to see whether it was present. The Gilbert *et al.* (14) task had no memory component, requiring the observer to find a target color that was identifiable only by being different from 11 identical distractors. These task differences could have introduced any number of unseen factors. Also the Daoutis *et al.* (16) and Gilbert *et al.* (14) experiments

differed in the former's including a target on only half the trials and in varying the number of distractors. Any of these differences may have contributed to the longer search times in Daoutis *et al.* (16) experiments.

The main conclusion we wish to emphasize here is that the reanalysis of the Daoutis *et al.* data (16) demonstrates a RVF relative advantage for across-category searches. Moreover, this applied to both separable and nonseparable searches despite considerable differences in their level of difficulty. This agrees with the Gilbert *et al.* (14) lateralization result and indicates the laterality effects may be quite general given the considerable differences in task. Note that the Daoutis *et al.* (16) study was not undertaken to test a lateralization hypothesis, and the lateralized effect was discovered only in post hoc analyses.

Visual Field Effects in a Color Detection Task with Sparse Displays. As part of a research program examining the development of categorical effects in color perception, Franklin *et al.* (8) developed a simple detection task that can be performed by infants. On each trial, a single circular target appears on a chromatically different, uniform background. In the initial infant study, detection time was measured by eye movements, taking advantage of the infants' natural inclination to look at the stimulus. In the current study, a manual response device was used instead, with the participants instructed to indicate whether the target was on the left or right by pressing a button with the corresponding index finger.

The target could appear in one of 12 locations arranged radially around the fixation cross, six to the left of fixation and 6 to the right of fixation, as in Gilbert *et al.* (14) (see Fig. 2b). The target differed from the background only in hue (constant value and chroma; see Fig. 2a) and was either in the same lexical category as the background (e.g., two blues: 5B, 10B; or two greens: 5BG, 10G) or in a different category (e.g., blue: 10BG; green: 5BG). The perceptual difference between target and

background was the same, in Munsell hue units, in the within-category and across-category cases. As in the Gilbert *et al.* study (14), the size of the perceptual separation varied, with hue step sizes of either 2.5 or 5 (see Fig. 2*a*).

There were very few incorrect responses ($\approx 4\%$). Median RTs for correct trials were calculated for each combination of category (within/across), perceptual distance (near/far), and visual field (LVF/RVF) for each observer, and these data were subjected to three-way repeated measures ANOVA. The only significant main effect was for category [$F(1, 23) = 58.83; P < 0.001$]. Across-category RTs were ≈ 60 ms faster than within-category RTs, indicating an overall category effect. As can be seen in Fig. 2*c*, there was also a strong interaction between category and visual field [$F(1, 23) = 26.85; P < 0.001$]. LVF targets were detected more quickly than RVF targets for within-category targets [$t(23) = 1.98; P = 0.060$, two-tailed]; for across-category targets, RVF targets were detected more quickly than LVF targets [$t(23) = 4.95; P < 0.001$]. There was a category effect for both visual fields, [minimum $t(23) = 3.72; P < 0.001$]; however, the size of the category effect (between faster than within) averaged 60 ms greater for the RVF than for the LVF [$t(23) = 5.18; P < 0.001$], and this held qualitatively for 22 of the 24 observers.

Perceptual distance had very little effect (see Fig. 2*d*). Targets with five-step separations were detected a modest 13 ms faster than those with 2.5-step separations, an effect that was marginally significant [$F(1, 23) = 3.58; P = 0.07$]. However, distance did interact with visual field [$F(1, 23) = 4.49; P < 0.05$] but not with category ($F < 1$). Five-hue step separations were ≈ 25 ms faster than 2.5 hue steps for the RVF [$t(23) = 2.48; P < 0.025$], whereas mean RTs for the two separations were virtually identical for the LVF. We do not have an explanation for this unexpected interaction.

With respect to the category–visual field relationship, these data mirror Gilbert *et al.*'s (14), with one exception. As noted above, in the Gilbert *et al.* study (14), a significant category effect (between faster than within) occurred only for RVF targets (although in each of the five conditions tested, LVF RTs showed a nonsignificant tendency in the same direction). In the present experiments, a significant category effect was found for both visual fields, with the effect larger for RVF targets than for LVF targets.

As a further test of the robustness and generality of the lateralization effect, we ran a second version of this detection experiment, using stimuli in the blue-purple region. Target-background pairs were either within-blue, within-purple, or between blue-purple. We only used separations of 2.5 Munsell hue steps, keeping value and chroma constant. Two-way ANOVA showed that the between-category search was ≈ 30 ms faster than within-category search [$F(1, 33) = 25.8; P < 0.001$] and that the interaction between visual field and category was significant [$F(1, 33) = 5.94; P < 0.025$]. Consistent with the blue-green results, the category effect was larger for the RVF than the LVF (Fig. 2*e*). The difference for the RVF was significant [$t(33) = 6.07; P < 0.001$], whereas the LVF difference was not significant [$t(33) = 1.23; P = 0.23$]. These results directly mirror those of Gilbert *et al.* (14), i.e., without the exception noted above.

General Discussion. Gilbert *et al.* (14) reported that a target color from a linguistic category distinct from that of distractors is found faster in the RVF than the LVF and, conversely, that a target color from the same named category as distractors is found faster in the LVF than the RVF. Because (i) each visual field projects to the contralateral brain hemisphere, (ii) the LH is known to favor language processing, and (iii) the lateralization effect was eliminated when concurrent demands were made on verbal, but not spatial, processing, Gilbert *et al.* (14) concluded they had isolated a Whorfian effect that was mostly or wholly restricted to the RVF/LH pathway. We report here that a similar

effect is observed in two different color perception tasks, indicating that the laterality effect is quite general.

The first approach involved a reanalysis of the Daoutis *et al.* (16) data. Using a color identification task, it was found that the categorical relationship of a memorized target to distractors influenced visual search time, independent of purely perceptual factors (linear separability in color space). The side of the display on which the target color appeared (when present) was not analyzed in the initial study. When reanalyzed, as we have done here, these data show an interaction of visual field with across-versus same-category trials, with a stronger category effect in the RVF than in the LVF. This difference is driven by a RVF disadvantage for within-category trials.

The second approach consisted of two new experiments, employing a detection task. The task was similar to that used by Gilbert *et al.* (14) except that there were no distractor stimuli; rather, the target color was presented against a uniformly colored background, and the categorical relationship of the target and background was manipulated. Again, we observed an interaction of visual field with across- versus same-category trials, with the RVF showing a relative advantage in search speed for across-category trials. These results support the earlier finding (14) that the RVF/LH pathway is the primary locus of category effects in color cognition and/or perception.

Our methods differ from those of Gilbert *et al.* (14) in several important respects. We used somewhat different tasks, although they were also speeded visual search tasks, and we tested different category boundaries. We examined the blue/purple, blue/green, and purple/pink boundaries, whereas Gilbert *et al.* (14) only examined the blue/green boundary. Given these differences in task and stimuli, our finding of stronger category effects in the RVF than in the LVF constitutes a confirmation, and generalization, of the Gilbert *et al.* (14) findings. In contrast, there is another point of difference that does not merely confirm the earlier findings: Whereas Gilbert *et al.* (14) found significant category effects in the RVF but not the LVF, we find significant effects in both visual fields, but stronger effects in the RVF. This difference raises the question of the source of this weaker LVF category effect. There are at least two possibilities. One is that it is based, like the RVF effect, on linguistic information, but in this case that information must travel across the corpus callosum to the RH, and its influence may be attenuated because of this transfer. Another intriguing possibility is that the LVF category effect is of an entirely different character and, instead, reflects presumably universal categorical distinctions that are present even in prelinguistic infants (7–8). These possibilities can be discriminated by determining whether LVF and RVF category effects both vary with the speaker's native language.

Taken as a whole, our findings largely confirm, but also qualify, the proposal that Whorfian effects are lateralized to the RVF. More broadly, our findings strengthen the notion that considerations of brain organization, which traditionally have not been brought to bear on the Whorf hypothesis, may be relevant to that debate.

Materials and Methods

Color Identification Task. Full details can be found in Daoutis *et al.* (16).

Participants. There were 8 participants in the first experiment (5 women and 3 men; mean age 28 years) and 12 in the second (6 women and 6 men; mean age 26 years). They were all staff or students at the University of Surrey.

Equipment and stimuli. The stimuli were displayed on a calibrated 15-inch Sony Trinitron monitor, and the CIE coordinates were measured with a Minolta CS100 chroma meter. There were two sets of three stimuli for each experiment, a within-category set and an across-category set. Within each set, luminance was constant, the stimuli were colinear in CIE $u' v'$, and the separation between

7. Franklin A, Davies IRL (2004) *Br J Dev Psychol* 22:349–377.
8. Franklin A, Pilling M, Davies IRL (2005) *J Exp Child Psychol* 91:227–248.
9. Özgen E, Davies IRL (2002) *J Exper Psychol Gen* 131:477–493.
10. Roberson D, Davidoff J (2000) *Mem Cognit* 28:977–986.
11. Roberson D, Davies IRL, Davidoff J (2000) *J Exp Child Psychol* 129:369–398.
12. Saunders BAC, van Brakel J (1997). *Behav Brain Sci* 20:167–179.
13. 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 A, Kirsh D (Lawrence Erlbaum, Mahwah, NJ).
14. Gilbert AL, Regier T, Kay P, Ivry RB (2006) *Proc Natl Acad Sci USA* 103:489–494.
15. Knecht S, Deppe M, Dräger B, Bobe L, Lohmann H, Ringelstein E-B, Henningsen H (2000) *Brain* 123:74–81.
16. Daoutis CA, Pilling M, Davies IRL (2006) *Vis Cogn* 14:217–240.
17. Duncan J, Humphreys GW (1989) *Psychol Rev* 96:433–458.