Object- and feature-based priming in visual search

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Two contrasting accounts for priming in visual search have been proposed. The main difference between the two is the level of perceptual processing at which the priming effects are assumed to occur, whether priming is assumed to operate through the selective facilitation of features or at the level of selection of objects for response. The aim of the experiments here was to contrast these accounts. In the first two experiments, observers performed a search for the odd diamond in the midst of two distractor diamonds. Each diamond had two colors, but the configurations of the colors within the diamonds were different for the two experiments in ways previously shown to lend themselves differently well to object formation. The results show that priming can be *both* feature- and object-based, depending on the topological properties of the stimuli. This was confirmed in a third experiment, in which a quite dissimilar stimulus set was used to address the same question, once again yielding similar results. We thus show that priming operates at various levels of perceptual processing, a result consistent with new findings from neuroimaging and neuropsychology.

Research on how we humans scan the visual field around us has often focused on bottom-up mechanisms that perform saliency-based computations of local feature contrasts and on guidance toward items or features that match an observer's goals (Egeth, Jonides, & Wall, 1972; Treisman & Gelade, 1980; Wolfe, 1994). The operation of such mechanisms is assumed to result in attentional selection of items for further analysis at a late, limited-capacity stage (see, e.g., Duncan, 1980).

Other studies have subsequently shown that search for a particular target is speeded if the same target has appeared on a previous trial (e.g., Geyer, Müller, & Krummenacher, 2006; Goolsby & Suzuki, 2001; Kristjánsson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1994; Olivers & Meeter, 2006; Treisman, 1992; Wang, Kristjánsson, & Nakayama, 2005), if the current target shares features with a preceding target (Kristjánsson, 2006b), or if the target appears in the same location as on a previous trial (Geng et al., 2006; Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005; Maljkovic & Nakayama, 1996).

Maljkovic and Nakayama (1994) argued that priming reflects facilitated processing of specific features, perhaps reflecting the operation of low-level perceptual memory (see, e.g., Magnussen, Greenlee, Asplund, & Dyrnes, 1991). On the other hand, Huang, Holcombe, and Pashler (2004; see also Hillstrom, 2000) argued that priming reflects facilitated processing of an episodic memory representation of the previous trial, speeding response selection. Response selection accounts of priming, however, have been strongly argued against by Sigurdardóttir, Kristjánsson, and Driver (in press).

Here we compared visual search performance for objects that have been shown to lend themselves differently to object-based processing (see, e.g., Allport, 1971). Wolfe, Friedman-Hill, and Bilsky (1994) found that *enclosure*, or whether one part of an object is enclosed within the confines of another (as in Figure 1B), determines whether targets in visual search are processed as single objects. Vogel, Woodman, and Luck (2001) then found that two colors of an object were more likely to be retained in visual working memory when one color was enclosed within the other.

To address the level at which priming effects occur, we contrasted search for two sorts of diamonds (see Figure 1). Observers searched for a diamond with a color combination different from that of two other diamonds. The diamonds in Experiment 1 had two colors on either side of the vertical midline (see Figure 1A); in Experiment 2, a small diamond of one color was enclosed within a larger one (see Figure 1B). The task in both experiments was to indicate whether there was a cutoff at the top or bottom of the target diamond with its odd color combination, relative to the two distractors, which had the same color combination as each other.

According to a pure feature-based account, we should see little difference in priming for the two diamond types. The largest priming effect should occur when both features are repeated, although a considerable effect should also occur when only one color is repeated. If priming occurs at a late stage, when objects are integrated, one should find priming only when both colors are repeated, and little or no priming when only one feature is repeated (an "all-or-none" priming pattern). However, according to a *hybrid*[1] view, in which it is assumed that both types of priming can occur, one might expect the priming pattern to depend, if the "enclosed" diamonds are more con-
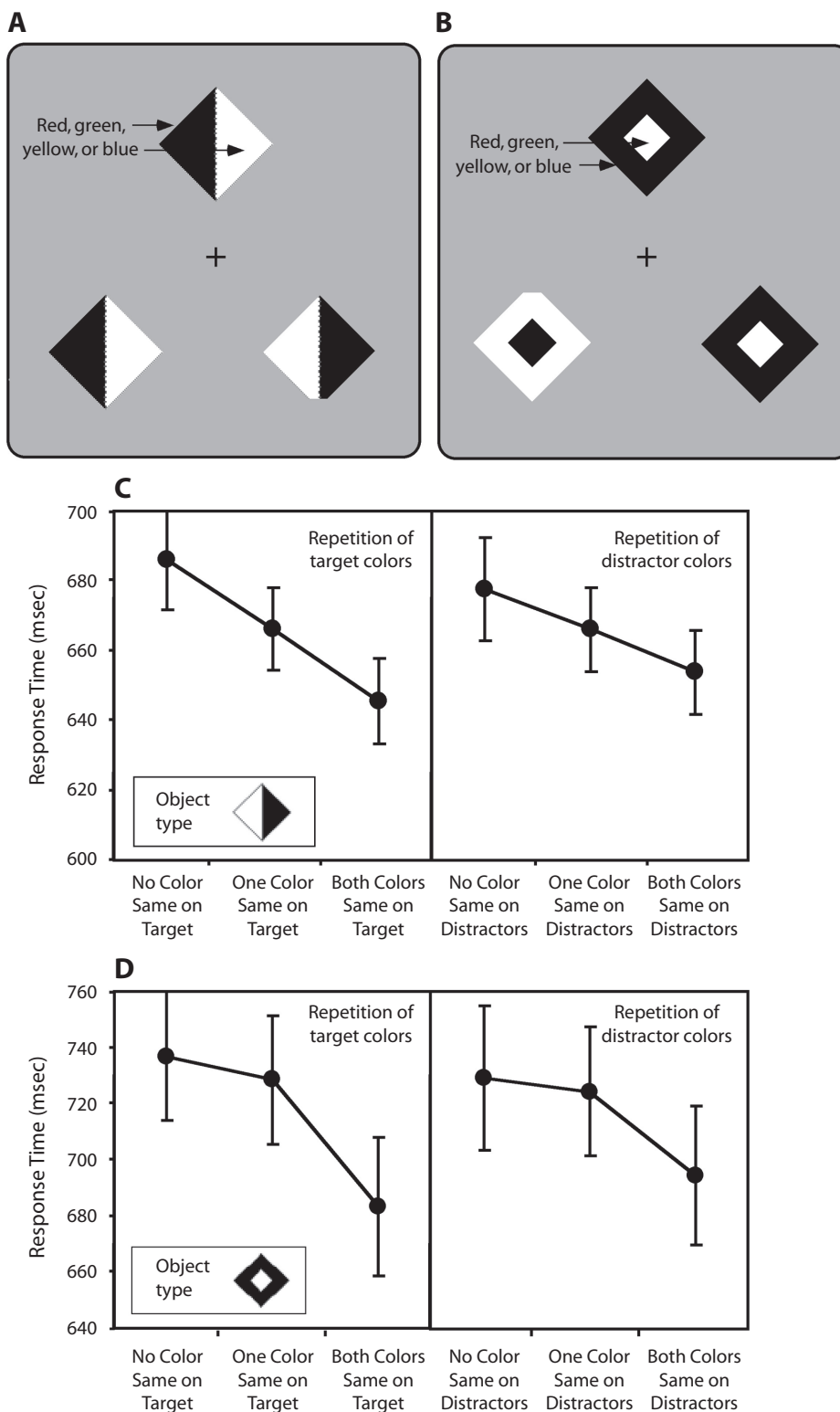

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Figure 1. The stimuli in Experiments 1 (panel A) and 2 (panel B), along with the results. The observers had to find the diamond that had a color combination different from that of the other two (at bottom right in panel A and bottom left in panel B) and then indicate whether the target diamond had a notch at the top or bottom (at bottom in panel A, at top in panel B). Panel C shows response times in Experiment 1 when no, one, or both colors were repeated on the target (left) and on the distractors (right). Panel D shows the response times from Experiment 2 as a function of color repetition on the target (left) and on the distractors (right). The error bars show standard errors of the means.

ducive to object-based processing, on whether the *whole object* is repeated. The vertically split diamonds might be less likely to be considered whole objects, so with those stimuli, repetition of one feature might suffice for priming; that would not be the case for the "enclosed" diamonds, in which priming should require the repetition of both features.

EXPERIMENT 1

Method

Participants. A total of 15 observers (8 male, 7 female, 22–42 years of age) participated. All had normal or corrected-to-normal vision, and tests indicated that all could easily distinguish the four colors used in the experiment. Each observer participated in 300 experimental trials, with at least 50 practice trials beforehand.

Stimuli and Procedure. The stimuli were presented on an 85-Hz CRT monitor controlled by a G4 Macintosh microcomputer running custom software prepared in C. The target and two distractor diamonds (2.4º × 2.4º) were presented on a dark gray (1.59 cd/m²) background. Each contained a different color on each side of its vertical midline. The four possible colors were red (41.4 cd/m²), green (55.8 cd/m²), yellow (97.8 cd/m²), and blue (35.8 cd/m²). The only constraint on the color combinations for any given trial was that the target and distractors could not have the *exact* same colors (i.e., the same combination of colors in the same positions). The stimuli were presented on an imaginary circle (radius 4.05º). The three stimuli were always in the same locations on the screen (as shown in Figure 1A), whereas the respective positions of the target and distractors were random for each trial.

Observers had their heads stabilized with a chinrest in order to vertically align eye position with the fixation point (viewing distance 54 cm). A trial started with the presentation of a fixation cross at screen center, followed 1,200–1,700 msec later (determined randomly on each trial) by the target and distractors, which were presented until response. Observers indicated by a keypress whether the oddly colored diamond had a notch (size 13′ of arc) at the top or the bottom, and they were encouraged to respond quickly without sacrificing accuracy. Auditory feedback was provided.

Results and Discussion

Trials with correct responses and response times (RTs) within three *SD*s of the mean were included in the analyses (95.7%). The mean RTs as a function of repetition of target and distractor colors (no, one, or both colors repeated from the preceding trial) are shown in Figure 1C. RTs decreased approximately linearly as target color was repeated; the effect when repeating one color was only slightly more than half the size of the effect when repeating both colors. The effects of distractor repetition were comparable, although they were smaller than the target repetition effect.

A 3 × 3 repeated measures ANOVA, with the factors repetition of color on target and on distractors, revealed a main effect of color repetition on the target [$F(2,28) = 8.5, p < .001$]. Post hoc *t* tests (Bonferroni corrected) revealed a close-to-significant difference between trials in which no color and trials in which one color was repeated [$t(14) = 2.29, p = .017$], as well as significant differences between repetition of no color and of both colors [$t(14) = 4.09, p = .001$] and between repetition of one color and of both colors [$t(14) = 3.123, p = .007$].

The effect of distractor repetition was significant [$F(2,28) = 3.83, p = .034$]. Post hoc *t* tests did not reveal significant differences between trials when no color was repeated and when one was [$t(14) = 1.49, p = .079$], when no color was repeated and when both were [$t(14) = 2.13, p = .026$], and when one color was repeated and when both were [$t(14) = 2.0, p = .033$], but the *p* values do suggest that the differences were close to significant at the conservative Bonferroni-corrected α level we used. There was no interaction between the effects of repetition of the target and the distractor colors [$F(4,56) = 0.668, p = .617$].

The results from Experiment 1 clearly challenge object/response accounts of priming, since repetition of the two colors led to *additive* effects. Strong versions of object- or response-based accounts argue that *both* colors of the target would need to be repeated for priming to occur. A more obvious conclusion is that the features on the diamonds led to independent and additive priming effects, a clear example of feature-based priming. In sum, the results are consistent with the feature-based and hybrid accounts of priming, not with object-based accounts.

EXPERIMENT 2

Wolfe et al. (1994) found large differences in visual search performance that depended on whether one of two colors on an object was enclosed within the other (see Figure 1). To test whether object-based priming would be more likely for such stimuli than for those in Experiment 1, in Experiment 2 we tested color priming for diamonds in which one part was enclosed within the other.

Method

The method was similar to that used in Experiment 1, except for the difference in color layout on the diamonds. Constraints on the possible color combinations for the target and the distractors were similar to those in Experiment 1. For example, on any given trial, the inner part of the target diamond could be blue and the outer part green, while the inner parts of the distractors were blue as well, but the outer parts were yellow. A total of 15 observers (4 male, 11 female) participated in 500 trials as well as 50 practice trials.

Results

Figure 1D shows the results. There is a fundamental difference from Experiment 1 in the pattern of the priming effects: A priming benefit only occurred if *both* colors of the diamonds were repeated, although a very small (nonsignificant, as shown below) repetition effect did occur if one color was repeated on either the target or the distractors.

A 3 × 3 ANOVA revealed a main effect of repetition of target colors [$F(2,28) = 15.7, p < .001$]. Post hoc *t* tests showed no significant difference between the conditions in which no colors were repeated on the target and those in which only one color was repeated [$t(14) = 1.15, p = .270$], but significant differences did emerge between repetition of both colors and repetition of only one [$t(14) = 3.95, p < .001$] and between repetition of no color and of both [$t(14) = 4.67, p < .001$].

The ANOVA also revealed a significant effect of repetition of color on distractors [$F(2,24) = 11.06$, $p < .001$]. Post hoc t tests showed significant differences between repetition on the distractors of neither color and of both colors [$t(14) = 4.88$, $p < .001$] and of both colors and only one [$t(14) = 3.17$, $p = .007$], but not between repetition of one color and of neither [$t(14) = 0.67$, $p = .51$]. No interaction occurred between the two factors [$F(4,56) = 0.963$, $p = .44$]. A final t test showed no difference between repetition of the inner versus the outer part when only one color was repeated [$t(14) = 0.73$, $p > .2$].

The results of Experiment 2 are thus fundamentally different from those of Experiment 1 and are consistent with both the object-based and hybrid accounts of priming, whereas Experiment 1 revealed a feature-based pattern. The obvious explanation for the observed results is the layout difference between the two types of diamonds.[2]

In sum, Experiment 1 revealed some hints of object-based priming, whereas Experiment 2 showed a strong object-based effect. The most parsimonious account of the data seems to be that priming can be both feature- and object-based, with the critical determining factor being the topological properties of the stimuli; this result supports the hybrid model, in which priming can be feature- or object-based, depending on the task.

EXPERIMENT 3

To further test the three predictions, we contrasted two quite different object types in Experiment 3 (types of "beach balls" from Xu, 2002b; see Figure 2A for examples). Xu (2002b) found that *conjunction* search (Treisman & Gelade, 1980) was considerably faster for beach balls in which only one part varied than it was when two parts
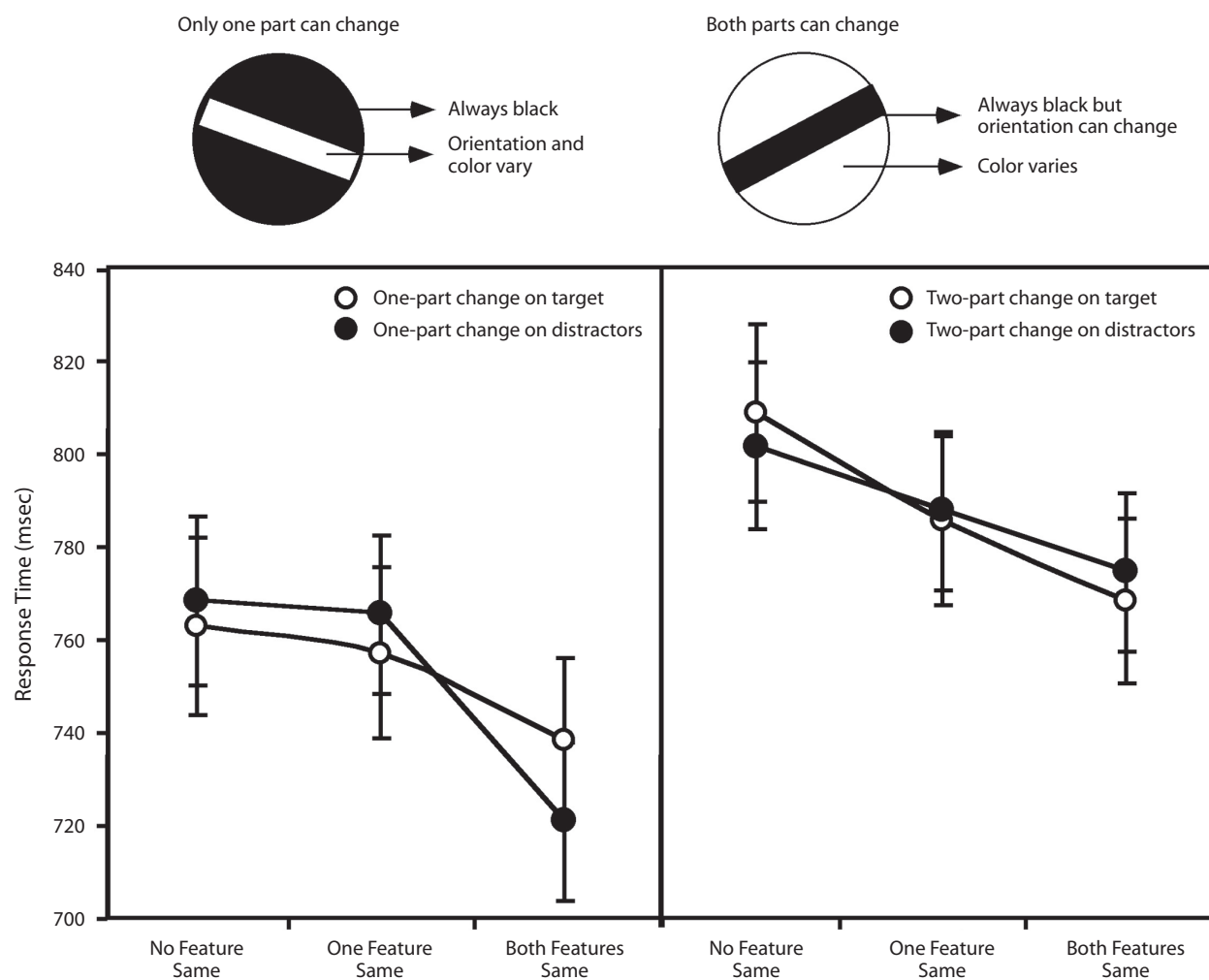

Figure 2. The "beach balls" used in Experiment 3, along with the results. The beach ball type on the left had only one part that could change (the bar, which changed in orientation and color), whereas both the background color and the orientation of the black (1.31 cd/m^2) stripe could change for the beach ball on the right. For the one-part-change beach balls, the disk was always black. For the two-part-change beach balls, the stripe was always black but could change in orientation, whereas the disk could change color. Panel B shows the results as a function of whether no features, one feature, or both features changed. Results for the one-part-change beach balls are shown on the left, and those for the two-part-change beach balls are on the right. The error bars show standard errors of the means.

varied. Similar differences were found for visual short-term memory (Xu, 2002a). Xu's (2002a, 2002b) findings indicate an object advantage for "one-part-change" beach balls, since the critical changes only occurred on one part of the object, the central bar.

We tested whether priming would be feature-based for two-part-change beach balls but object-based for one-part-change beach balls. Observers searched for an "odd" beach ball in the display (among four distractor beach balls). In the one-part-change case, the target was the beach ball with an oddly colored *and* oriented bar. In the two-part-change case, the observers had to find the beach ball with an odd combination of background color and bar orientation.

Method

Five beach balls were presented on each trial, one target and four distractors (two with a different color, the other two a different orientation), on an imaginary circle (radius 4.23°) with a fixation point at screen center. The diameter of the beach balls was 2.36°. On any given trial, the observers searched for the target with the odd combination of color and bar orientation. The task was to indicate whether the bar on the target beach ball was rotated clockwise or counterclockwise (by 30°) from horizontal. A total of 8 observers (3 male, 5 female) participated in 800 trials each, or four blocks of 100 trials for each beach ball type, run in counterbalanced order. The method was otherwise similar to that of Experiment 1, except for the light gray background (43.2 cd/m²).

Results and Discussion

Search was, overall, faster for the one-part-change beach balls, consistent with Xu (2002b). For the one-part-change beach balls, a clear object-based priming pattern was seen, both for the target and the distractors; a significant effect of repetition was only seen when both features were repeated. On the other hand, priming was additive for two-part-change beach balls. This was confirmed with a three-way ANOVA, which showed significant effects of target repetition [$F(2,14) = 8.97$, $p = .004$], distractor repetition [$F(2,14) = 11.13$, $p = .001$], and beach ball type [$F(1,7) = 13.67$, $p = .008$]. Significant interactions occurred between target repetition and beach ball type [$F(2,14) = 9.57$, $p = .002$] and between distractor repetition and beach ball type [$F(2,14) = 16.97$, $p < .001$], which confirmed differential effects of repetition for the two stimuli. Neither the interaction between the two repetition types nor the three-way interaction was significant.

Post hoc *t* tests at Bonferroni-corrected α levels (see Tables 1 and 2) confirmed that the priming pattern was object-based for the one-part-change beach ball (both features had to be repeated for priming) and feature-based for the two-part-change beach ball (significant priming was also found when only one feature was repeated). When only one feature changed, post hoc *t* tests for differences in priming that depended on the changing feature showed that only the priming pattern for the one-part-change beach balls was different when color versus orientation was repeated. Orientation repeated on its own did *not* lead to priming, for either targets or distractors (all $ps > .2$), whereas color repetitions did prime targets [$t(7) = 2.97$, $p = .01$] but not distractors.

Table 1
t Values for Post Hoc Tests of the Differences Between the Different Repetition Types for the One-Part-Change Objects in Figure 2

	Repetition on Target		Repetition on Distractors	
	t	p	t	p
No repetition vs. one repetition	0.77	.205	1.16	.143
No repetition vs. two repetitions	3.47	.007*	5.87	<.001*
One repetition vs. two repetitions	4.21	.002*	4.76	.001*

Note—$df = 7$ for all *t* tests; α level set at .008 (with Bonferroni correction).   *Significant at the Bonferroni-corrected α level.

Table 2
t Values for Post Hoc Tests of the Differences Between the Different Repetition Types for the Two-Part-Change Objects in Figure 2

	Repetition on Target		Repetition on Distractors	
	t	p	t	p
No repetition vs. one repetition	4.03	.003*	3.35	.006*
No repetition vs. two repetitions	7.18	<.001*	6.01	<.001*
One repetition vs. two repetitions	3.12	.007*	2.73	.016

Note—$df = 7$ for all *t* tests; α level set at .008 (with Bonferroni correction).   *Significant at the Bonferroni-corrected α level.

The results of Experiment 3 provide further evidence that both object- and feature-based priming can occur, and which pattern occurs depends on the stimuli in each case. Roughly, the priming pattern was object-based for two-part-change beach balls and feature-based for one-part-change beach balls. An interesting aspect of these results is the difference between color and orientation repetition on the one-part-change beach ball targets; repetition of color, on its own, led to priming, but orientation repetition did not. One possible reason is that the colored stripe against the dark gray background was particularly salient, which may have broken down the "objectness" of those beach balls when they served as targets. Consistent with this interpretation, Xu (2002b, Figure 3) found that search for the beach balls was faster when color was the target-defining feature, indicating that color was more salient than orientation for stimuli of this sort.

Overall, the results only strengthen our conclusion that whether or not priming is object-based depends on the type of stimulus in each case.

GENERAL DISCUSSION

Does priming operate on separate features or on whole objects? The answer seems to depend on the stimuli. Stimuli conducive to object-based processing are more likely to lead to object-based priming. They show roughly an all-or-none priming pattern, whereas priming is more piecemeal for stimuli that do not form objects as easily.

This fundamental difference is clearly not predicted by strong versions of either feature- or object-based accounts of priming. Huang et al. (2004) argued that priming reflects facilitation at a late stage in which responses are selected on the basis of episodic memory representa-

tions of the preceding trials, thus reflecting priming of whole objects. Huang et al.'s observers searched for an odd-sized target among distractors and reported its orientation. When a same-sized target was repeated, search was faster if target color (which was independent of the task) was also repeated, but when target size changed, repeating the color actually *harmed* performance. Priming from size repetition was thus modulated by whether target color was repeated or not. This result was seemingly inconsistent with Maljkovic and Nakayama's (1994) claim that the attended *feature* was selectively facilitated.

Kristjánsson (2006b) tested whether simultaneous priming would occur in single-feature search for three-featured (orientation, spatial frequency, and color) Gabor patches. The different features showed independent priming that was not dependent on whether the whole object was repeated, but the pattern of priming was not uniform for the different features. Thus, separate features can prime independently, but the nature of the features determines whether or not they show independent priming. This may indicate that the stimuli used by Huang et al. (2004) simply lent themselves well to object-based processing—with priming occurring only when the whole object was repeated.

The present results also show that priming is not always tied to single features, as a strict interpretation of the proposal of Maljkovic and Nakayama (1994) would entail. Rather, the results argue for a hybrid view, in which the topological properties of the stimuli are assumed to determine whether priming is feature- or object-based.

By using fMRI, Kristjánsson, Vuilleumier, Schwartz, Macaluso, and Driver (2007) found distinct neural effects for repetition of target color in areas traditionally associated with color processing, as well as position-related effects in parietal areas (often thought to be involved in spatial attentional selection; see also Geng et al., 2006); however, they also found distinct effects in anterior fusiform cortex only seen when a *same-colored target* appeared in the *same position*. Considerable overlap in modulation of activity for color and position repetition was found in frontoparietal regions known to be involved with selective attending, consistent with proposals that priming affects attention deployment (see, e.g., Kristjánsson, 2006a; Kristjánsson & Nakayama, 2003). Kristjánsson et al. (2005) tested color and position priming on neglect patients and found a dissociation, in that position priming was more disrupted by parietal lesions.

These results indicate that priming can occur at more than a single level in the perceptual hierarchy (see also Campana, Cowey, & Walsh, 2006, for converging evidence from transcranial magnetic stimulation studies). In light of this evidence from cognitive neuroscience, as well as from the results here, views that priming reflects only one particular process are likely to fail.

Conclusions

Priming can be both feature- and object-based, and which of the two occurs may be a simple function of the configuration of features on the stimuli. Thus, a hybrid view, in which priming is conceived of as reflecting facilitation of feature- and/or object-based processing, seems the most parsimonious account of the available evidence.

REFERENCES

ALLPORT, D. A. (1971). Parallel encoding within and between elementary stimulus dimensions. *Perception & Psychophysics*, **10**, 104-108.

CAMPANA, G., COWEY, A., & WALSH, V. (2006). Visual area V5/MT remembers "what" but not "where." *Cerebral Cortex*, **16**, 1766-1770.

DUNCAN, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, **87**, 272-300.

EGETH, H., JONIDES, J., & WALL, S. (1972). Parallel processing of multi-element displays. *Cognitive Psychology*, **3**, 674-698.

GENG, J. J., EGER, E., RUFF, C. C., KRISTJÁNSSON, Á., ROTSHTEIN, P., & DRIVER, J. (2006). On-line attentional selection from competing stimuli in opposite visual fields: Effects on human visual cortex and control processes. *Journal of Neurophysiology*, **96**, 2601-2612.

GEYER, T., MÜLLER, H. J., & KRUMMENACHER, J. (2006). Cross-trial priming in visual search for singleton conjunction targets: Role of repeated target and distractor features. *Perception & Psychophysics*, **68**, 736-749.

GOOLSBY, B. A., & SUZUKI, S. (2001). Understanding priming of color-singleton search: Roles of attention at encoding and "retrieval." *Perception & Psychophysics*, **63**, 929-944.

HILLSTROM, A. P. (2000). Repetition effects in visual search. *Perception & Psychophysics*, **62**, 800-817.

HUANG, L., HOLCOMBE, A. O., & PASHLER, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition*, **32**, 12-20.

KRISTJÁNSSON, Á. (2006a). Rapid learning in attention shifts: A review. *Visual Cognition*, **13**, 324-362.

KRISTJÁNSSON, Á. (2006b). Simultaneous priming along multiple feature dimensions in a visual search task. *Vision Research*, **46**, 2554-2570.

KRISTJÁNSSON, Á., & NAKAYAMA, K. (2003). A primitive memory system for the deployment of transient attention. *Perception & Psychophysics*, **65**, 711-724.

KRISTJÁNSSON, Á., VUILLEUMIER, P., MALHOTRA, P., HUSAIN, M., & DRIVER, J. (2005). Priming of color and position during visual search in unilateral spatial neglect. *Journal of Cognitive Neuroscience*, **17**, 859-873.

KRISTJÁNSSON, Á., VUILLEUMIER, P., SCHWARTZ, S., MACALUSO, E., & DRIVER, J. (2007). Neural basis for priming of pop-out during visual search revealed with fMRI. *Cerebral Cortex*, **17**, 1612-1624.

KRISTJÁNSSON, Á., WANG, D., & NAKAYAMA, K. (2002). The role of priming in conjunctive visual search. *Cognition*, **85**, 37-52.

MAGNUSSEN, S., GREENLEE, M. W., ASPLUND, R., & DYRNES, S. (1991). Stimulus-specific mechanisms of visual short-term memory. *Vision Research*, **31**, 1213-1219.

MALJKOVIC, V., & NAKAYAMA, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, **22**, 657-672.

MALJKOVIC, V., & NAKAYAMA, K. (1996). Priming of pop-out: II. Role of position. *Perception & Psychophysics*, **58**, 977-991.

OLIVERS, C. N. L., & MEETER, M. (2006). On the dissociation between compound and present/absent tasks in visual search: Intertrial priming is ambiguity driven. *Visual Cognition*, **13**, 1-28.

SIGURDARDÓTTIR, H. M., KRISTJÁNSSON, Á., & DRIVER, J. (in press). Repetition streaks increase perceptual sensitivity in visual search of brief displays. *Visual Cognition*.

TREISMAN, A. [M.] (1992). Perceiving and re-perceiving objects. *American Psychologist*, **47**, 862-875.

TREISMAN, A. M., & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.

VOGEL, E. K., WOODMAN, G. F., & LUCK, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 92-114.

WANG, D., KRISTJÁNSSON, Á., & NAKAYAMA, K. (2005). Efficient visual search without top-down or bottom-up guidance. *Perception & Psychophysics*, **67**, 239-253.

WOLFE, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.

WOLFE, J. M., FRIEDMAN-HILL, S. R., & BILSKY, A. B. (1994). Parallel processing of part–whole information in visual search tasks. *Perception & Psychophysics*, **55**, 537-550.

XU, Y. (2002a). Encoding color and shape from different parts of an object in visual short-term memory. *Perception & Psychophysics*, **64**, 1260-1280.

XU, Y. (2002b). Feature integration across parts in visual search. *Perception*, **31**, 1335-1347.

NOTES

1. This view is *hybrid* only in the sense that both object/response priming and feature priming can occur; it does not assume that both types of processes would necessarily occur *in conjunction* in any particular task.

2. A 2 (Experiment 1 or 2) $\times$ 3 (repetition of 0, 1, or 2 target colors) $\times$ 3 (repetition of 0, 1, or 2 distractor colors) repeated measures ANOVA comparing the data for the two experiments showed a strong three-way interaction [$F(4,56) = 23.35$, $p < .001$], confirming that the two types of stimuli resulted in different patterns of priming.