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The return of object-based attention: Selection of multiple-region objects

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Objects can control the focus of attention, allowing features on the same object to be selected more easily than features on different objects. In the present experiments, we investigated the perceptual processes that contribute to such object-based attentional effects. Previous research has demonstrated that object-based effects occur for single-region objects but not for multiple-region objects under some conditions (Experiment 1, Watson & Kramer, 1999). Such results are surprising, because most objects in natural scenes are composed of multiple regions. Previous findings could therefore limit the usefulness of an object-based selection mechanism. We explored the generality of these single-region selection results by manipulating the extent to which different (i.e., multiple) regions of a single object perceptually grouped together. Object-based attentional effects were attenuated when multiple regions did not group into a single perceptual object (Experiment 1). However, when multiple regions grouped together based on (1) edge continuation (Experiments 2 and 3) or (2) part and occlusion cues (Experiment 4), we observed object-based effects. Our results suggest that object-based attention is a robust process that can select multiple-region objects, provided the regions of such objects cohere on the basis of perceptual grouping cues.

Since the late 1970s, spatial metaphors such as spotlights (B. A. Eriksen & C. W. Eriksen, 1974; Posner, 1980), zoom lenses (C. W. Eriksen & St. James, 1986; C. W. Eriksen & Yeh, 1985), and gradients (Downing & Pinker, 1985; LaBerge & Brown, 1989) have been used to describe how attention is distributed in the visual field. These space-based models of visual attention reasonably account for many attentional phenomena. However, over the past two decades, a wealth of studies have provided evidence that visual attention can also select objects. Observers can identify two attributes of a single object more accurately than two attributes of two different objects (Awh, Dhaliwal, Christensen, & Matsukura, 2001; Duncan, 1984; Kramer, Weber, & Watson, 1997; Lee & Chun, 2001; Vecera, 1997; Vecera & Farah, 1994). Observers can also detect targets in a cued (i.e., attended) object faster than those in an uncued object (e.g., Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998; Pratt & Sekuler, 2001; Vecera, 1994). The overwhelming consensus is that object-based and location-based attention coexist. Thus, both object-based and space-based attention represent different control settings for visual attention. The focus of attention can be controlled by either objects or locations.

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Recent theoretical accounts of object-based attention have attempted to link these object-based control processes with the perceptual grouping processes that define the perceptual objects selected by attention. Many views of object-based attention subscribe to some form of the grouped array hypothesis proposed by Vecera and Farah (1994; Vecera, 1994, 1997). This hypothesis explains object-based attention as resulting from selection from an array format (i.e., spatially formatted) representation, in which the locations and features have been grouped according to gestalt principles of perceptual organization. Watson and Kramer (1999) developed a strong theoretical framework for such a view of object-based attention by connecting object-based attention to Palmer and Rock's (1994; see also Palmer, 1999, 2002) influential theory of perceptual organization. Palmer and Rock's (1994) theory emphasized the role of uniform connectedness in perceptual organization. Uniform connectedness is the perceptual grouping principle stating that regions formed by uniform visual properties (luminance, color, or texture) tend to be organized as a single perceptual unit. Palmer and Rock suggested that uniform connectedness was an entry-level process in vision that formed the basis for later visual processes, including figure–ground assignment and part decomposition.

Working from the premise that uniform connectedness is an entry-level process that, in principle, affects all visual processes that follow, Watson and Kramer (1999) examined whether objects composed of a single region (i.e., uniformly connected objects composed of a single color, luminance, and texture) served as the basic units selected by object-based attention. If so, object-based attentional effects would be observed for such single-region objects but not for multiple-region objects. Watson and Kramer's (1999) displays contained a pair of wrenches similar to those shown in Figure 1. The wrenches were either uniformly gray (the single-region condition) or had a colored handle that separated the two ends of the wrench (the multiple-region condition). The observers' task was to search the two wrenches to determine whether one or two task-relevant features appeared in the display. One feature was a bent wrench end and the other was an open wrench end. When both features appeared, they could appear on one wrench (the same-object condition) or on both wrenches (the different-object condition).

Watson and Kramer (1999) demonstrated a strong object-based effect with single-region objects; observers detected two target features significantly faster when they appeared within one object rather than in two different objects. However, this object-based effect disappeared with multiple-region objects; observers detected the two target properties in approximately the same amount of time whether they appeared within one object or in two different objects. Thus, Watson and Kramer concluded that uniform connectedness formed the default representation of object-based attention. For object-based attention to operate, objects had to be composed of single regions of luminance, color, or texture. Any break in this single uniform region, such as the placement of a different-colored part, would prevent object-based attention from either being spread across the object or shifted within the object (but see Lamy & Egeth, 2002, for an alternate view).

Watson and Kramer (1999, Experiment 2) also reported that object-based effects were observed for multiple-region objects when all of the regions were task relevant. In their Experiment 2, Watson and Kramer suspected that the absence of object-based effects for multiple-region objects might have resulted because of the nature of the task rather than because of the surface structure of the wrench stimuli. Specifically, perceiving multiple-region objects as single entities was not necessary for observers to search target features in the display. Watson and Kramer asked observers to be engaged in the occasional probe task following the primary feature search task in order to encourage them to select the wrenches as unitary objects. Under this condition, in which attending to handle parts was necessary to complete the task, an object-based effect was observed for multiple-region objects.

When neither task relevance nor multiple-region priming was involved, the results of Watson and Kramer's Experiment 1 were clear-cut. In the absence of top-down information, object-based attention does not select multiple-region objects. These results pose a significant problem for the usefulness of object-based attention. If object-based attention operates only on objects composed of single regions, then this selection process is highly limited, because most objects in natural scenes are composed of multiple regions. Real-world objects contain multiple parts, each with different colors or luminance, and objects in natural scenes often overlap and partially occlude one another.[1] If object-based selection of attention selects only

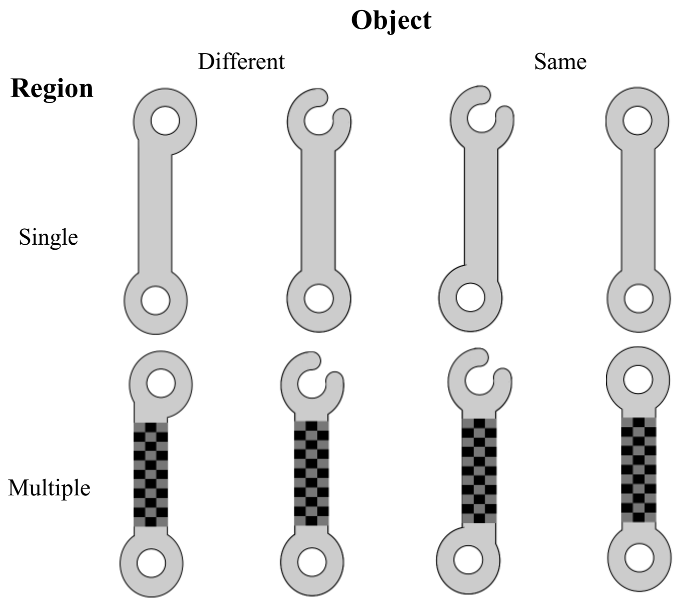

Figure 1. Stimuli similar to those from Experiment 1 in Watson and Kramer (1999). The observers searched the display for the presence of two target features: an open end (shown on the upper left pair, the upper end of the right wrench) and a bent end (shown on the upper left pair, the upper end of the left wrench). Watson and Kramer found an object-based effect in the single-region objects, but not in the multiple-region objects.

single-region objects, then there are an overwhelming number of objects that this selection mechanism does not select. Further, the results of several studies seem directly at odds with the idea that object-based attention selects only single-region (i.e., uniformly connected) objects. When an otherwise uniform, single-region object is occluded, the projection of that object is broken by the occluder, which creates the projection of multiple-region objects. Importantly, object-based attention appears to be able to select partially occluded objects (Behrmann, Zemel, & Mozer, 1998; Moore et al., 1998; Pratt & Sekuler, 2001), even if the occluder is irrelevant to the task. These studies suggest that object-based attention can select some multiple-region objects even when only bottom-up cues (i.e., surface structure) are available without any top-down effects (i.e., task relevance or multiple-region priming).

These considerations highlight the fact that the object-based attention literature is unclear as to when single-region objects dominate selection and when multiple-region objects can be selected, in the event that neither top-down information of object-based selection (task relevance) nor objects' geometrical structural cues (curvature of an object) are available. Given this ambiguity in the empirical record, we were interested in understanding the perceptual cues that could affect when object-based attention selects multiple-region objects and single-region objects.

To address this issue, we have focused on stimulus properties (i.e., image-based or bottom-up cues) that can allow multiple regions to be bound or grouped together into a single perceptual object. A close examination of Watson and Kramer's (1999) wrench stimuli suggests that the large checkerboard pattern on the handle surface might have prevented the edge of the handle from grouping with the edge of the wrench ends. The checkerboard-patterned handle was made of visibly different-colored regions, and the individual color patches of the checkerboard might not have grouped together as a single part because of the patches' color differences. Grouping via color similarity is a well-known gestalt grouping cue (Baylis & Driver, 1993; Kramer & Jacobson, 1991; Wertheimer, 1923/1958), and the use of highly dissimilar colors could have produced a discontinuous contour at the edge of the handle. This discontinuous edge may have prevented the handle's edge from grouping as a single contour and prevented grouping with the edge of the gray wrench ends, thus preventing the multiple regions from being grouped into a single perceptual object.

In five experiments, we explored the grouping properties that contribute to the selection of multiple-region objects. Before we could address the grouping hypothesis of multiple-region object selection, it was critical that we first replicate Watson and Kramer's (1999) results. Specifically, we needed to demonstrate that we could abolish object-based effects with multiple-region objects. In Experiment 1, we used wrench stimuli similar to those used by Watson and Kramer. Most importantly, the wrench handles had a large checkerboard pattern that was easily visible to our observers. To preview our results, we replicated Watson and Kramer's findings: Object-based effects occurred for single-region objects but not for multiple-region objects. In our subsequent experiments, we systematically demonstrated that object-based effects returned when explicit perceptual grouping cues were available within multiple-region objects. Specifically, when the contour of the handle perceptually grouped with the contour of the wrench ends, multiple-region wrenches were perceived as single perceptual objects, and object-based effects were observed. Even though perceptual grouping manipulations used in this study allowed the object-based attention to select multiple-region objects, we did not collect any explicit report data on observers' perceptual grouping of the wrench stimuli because of potential difficulties with explicit reports, such as demand characteristics. Instead, we relied on object-based attention effects to provide an implicit measure of grouping (see Beck & Palmer, 2002, for an example of using object-based attention to implicitly measure perceptual grouping). When items perceptually group with one another, these items are selected as a unit, and this unit is responded to more efficiently than are items that do not perceptually group with one another. Thus, if the wrench ends are grouped with the handle, we should observe object-based effects.

EXPERIMENT 1

To replicate Watson and Kramer's (1999) results, we had observers search for two target features; one feature or both features could appear in a display, and the observers reported whether one or two features were present. The relevant condition was when two features were present because these features occurred on either the same object or different objects. Object-based effects were defined by faster responses to same-object than to different-object trials.

Method

Participants. The observers were 28 University of Iowa undergraduates who received either course credit or payment; all were between the ages of 18 and 30 years and reported having normal or corrected-to-normal vision.

Stimuli. Stimuli were viewed from a distance of 60 cm and were presented on a 17-in. color monitor. The observers sat at individual booths in a well-lit room and viewed the stimuli binocularly.

Examples of the stimuli appear in Figure 2A. At the specified viewing distance, the wrench display subtended 16º to each side, with an 8.5º separation between the interior edges of the closest different-object wrench ends. Each wrench end had a diameter of 4.5º, and the shaft was 1.7º wide. On presentations in which a bent end was present, the bent end was 1.1º closer to the opposing wrench, reducing the end measurement to 14.9º and reducing the separation between the two different wrench ends to 7.4º. Wrench ends were centered to a point approximately 9.3º from fixation. The gap in the open end of the wrench subtended 1.24º at its minimum separation point. The handle, when present, was 6.4º in length.

For the single-region wrenches, the entire wrench was filled with light gray ($x = .299$, $y = .276$, 33 cd/m^2). However, for the multiple-region wrenches, the two wrench ends were the same light gray and the center of the shaft was occupied by a red-and-blue checkerboard pattern (Figure 2A) (red: $x = .521$, $y = .261$, 13 cd/m^2; blue: $x = .177$, $y = .072$, 6.8 cd/m^2).

Procedure. In each trial, the observer triggered the display by pressing a single key on a Cedrus four-button response box. Then, the

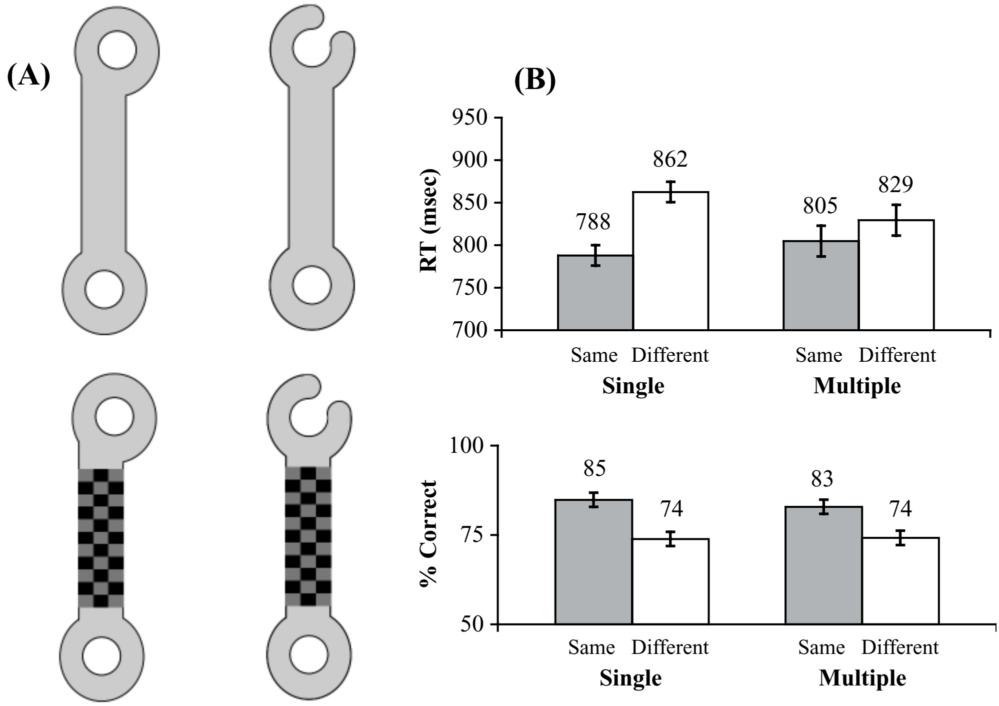

Figure 2. (A) An example of stimuli from Experiment 1: A single-region wrench pair on the top and a multiple-region wrench pair on the bottom. The handle part had a red-and-blue checkerboard pattern. (B) Experiment 1: Mean RT (msec) for correct responses (top) and accuracy (percent correct; bottom) on the function of object type and stimulus type. For all of the experiments, error bars represent 95% within-confidence intervals (Loftus & Masson, 1994). The data are collapsed across the vertical and horizontal orientation conditions.

text "ready?" appeared for 1,000 msec, followed by a fixation cross for 1,000 msec. After fixation, the stimulus display was presented for 150 msec on a white background, followed by a blank screen, which remained until the observer responded. The observer searched the display for an open end and a bent end. In each trial, one or both of these targets could appear; the observer made one response if only one target was found and the alternate response if both targets were found. When both targets were present, they appeared either at opposite ends of the same object or horizontally separated in different objects; the two features did not appear diagonally opposite one another in the different-object condition. Half of the trials had two targets (i.e., both bent and open ends) present and half of the trials had only one target (i.e., either a bent end or an open end) present.

Each observer performed a single experimental session. At the beginning of the session, the observers were presented with written as well as verbal instructions from the experimenter. The observers completed two phases of practice blocks before their participation in six experimental blocks. Each practice block consisted of 16 trials with eight single-region and eight multiple-region stimuli. In the first phase, the stimuli remained visible on the computer screen until an observer made a response. When the observers completed a first-phase block with 100% accuracy, the second phase of practice blocks was started. It typically took two blocks for the observers to reach 100% accuracy. In the second phase, the stimuli were presented for only 150 msec. When an observer completed a second-phase block with approximately 75% accuracy, the experimenter initiated six experimental blocks. It typically took one to two blocks for the observers to reach 75% accuracy. Out of six experimental blocks, three blocks contained only single-region wrenches, whereas the other three blocks contained only multiple-region wrenches. These blocks with the two wrench types were alternated across the six blocks. Half of the observers started with the single-region block; the other half started with the multiple-region block.

The observers performed 384 trials in six 64-trial experimental blocks. The observers were instructed to maintain their accuracy above 75% and to respond as quickly as possible.

Pairs of wrench stimuli were presented horizontally for half of the trials and vertically for the other half of the trials. The orientation of the wrenches (horizontal or vertical) was collapsed for the data analysis because preliminary analyses indicated that there was no statistical difference between these conditions.

Results and Discussion

As did Watson and Kramer (1999), we focused on the trials in which both of the target properties were present, because it was only for these trials that the classification of the same- or different-object condition was defined. We removed reaction times (RTs) that were beyond 3 *SD*s from the mean RT of each of the four experimental conditions. This trimming removed less than 1.4% of the total number of RTs. Although we focused on the trials with both target properties, for the sake of completeness, we present RTs of the trials with a single feature (either open or bent end) for all five experiments in Table 1.

Mean RTs and accuracy for trials with both targets present are presented in Figure 2B. A two-way repeated measures ANOVA with object type (same vs. different objects) and stimulus type (single vs. multiple regions) was performed on the mean RTs and accuracies. For RT, there was

Table 1
Mean Reaction Times (RTs, in Milliseconds) and Standard Errors for Trials With Single-Feature Targets

	Stimulus Type	RT Mean	RT *SE*
Experiment 1	Single	794	221
	Multiple	809	228
Experiment 2	Single	817	180
	Multiple	827	169
Experiment 3A	Single	764	163
	Multiple	769	144
Experiment 3B	Single	761	186
	Multiple	795	195
Experiment 4	Single	782	156
	Multiple	793	167

a main effect of object type, with faster RTs to same-object trials (796 msec) than to different-object trials (846 msec) [$F(1,27) = 16, p < .0005$]. The main effect of stimulus type was not significant, with similar RTs to the single-region objects (825 msec) and the multiple-region objects (817 msec) [$F(1,27) = 0.2, p > .7$]. Finally, the two-way interaction between object type and stimulus type was significant [$F(1,27) = 9, p < .007$]. The size of the object-based effect (same-object condition vs. different-object condition) was significantly larger for single-region objects (75 msec) than for multiple-region objects (25 msec). Planned pairwise comparisons indicated that the difference between the same- and different-object trials was significant for the single-region stimuli [$t(27) = 6, p < .0005$] but not for the multiple-region stimuli [$t(27) = 1, p > .2$].

For the accuracy data, there was a main effect of object type [$F(1,27) = 28, p < .0005$]. However, neither the main effect of stimulus type nor of two-way interaction was significant [$F(1,27) = 1, p > .3$ and $F(1,27) = 0.3$, $p > .6$, respectively].

The results of Experiment 1 replicated Watson and Kramer's (1999) uniform region effects: The observers exhibited object-based selection for single-region objects (i.e., gray wrenches) but not for multiple-region objects (i.e., wrenches with handles). There was a hint of an object-based effect in our multiple-region condition; this object-based effect was not statistically significant, and it was significantly smaller than the object-based effect in the single-region condition.

Having replicated the finding of smaller object-based effects for multiple-region objects, we now turn to the source of this finding. As we discussed earlier, this multiple-region effect is a limiting factor for object-based attention, given that most objects in natural scenes are composed of multiple regions and that objects are frequently occluded. A close inspection of Watson and Kramer's stimuli and our own stimuli revealed one possible cause of the multiple-region effect. We hypothesized that one cause of the disappearance of object-based effects in multiple-region objects was the weak perceptual grouping cues between the different regions. That is, the different regions (i.e., the wrench ends and the handle) may group together weakly if there is no appropriate perceptual cue. In both our stimuli and Watson and Kramer's, the handle with the red-and-blue checkerboard pattern created an edge discontinuity in the outline shape of the object. The red and blue regions were large enough to be perceived as discernibly different, and these individual patches failed to group with one another because they violated gestalt grouping by color similarity. The consequence of this failure was a weak perceptual grouping along with the edge of the handle. This weak grouping might have prevented the edge of the wrench ends from grouping with the handle. Based on this failed edge-grouping hypothesis, we predicted that encouraging grouping between multiple regions by providing appropriate grouping cues should allow object-based effects to return in multiple-region objects. We tested this hypothesis in the following four experiments.

EXPERIMENT 2

Because we suspected that the large-scale handle pattern in Experiment 1 might have prevented the handle's contour from grouping with the contour of the gray wrench body, we attempted to encourage edge grouping by reducing the size of the handle's checkerboard pattern. Reducing the checkerboard size would allow the edge of the handle to be perceived as a single contour that was coterminous with the edge of the wrench ends. If the edges of multiple regions group in the manner described, then attention should easily spread within or switch to the connected regions and result in an object-based effect. Therefore, we predicted a return of object-based attentional effects for the multiple-region wrenches used in Experiment 2.

Method

Participants. The observers were 28 University of Iowa undergraduates who received either course credit or payment; all were between 18 and 30 years of age and reported having normal or corrected-to-normal vision. None of the observers participated in any of the other experiments reported in the present article.

Stimuli and Procedure. The multiple-region stimuli used in Experiment 2 were identical to those used in Experiment 1, with the exception of the different size of the handle's checkerboard pattern (see Figure 3A): The size of each square was 4 $\times$ 4 pixels (in comparison with 18 $\times$ 18 pixels used in Experiment 1). When viewed from a distance of 60 cm, this pattern was perceived as a single purple region. The procedure was identical to that in Experiment 1.

Results and Discussion

The data were treated as they were in Experiment 1. Trimming RTs over 3 *SD*s above each condition mean removed less than 2.1% of the overall RTs. Mean RTs and accuracies are presented in Figure 3B. A two-way repeated measures ANOVA with object type (same vs. different objects) and stimulus type (single vs. multiple regions) was performed on the mean RTs and accuracies. For RT, there was a main effect of object type [$F(1,27) = 28, p < .0005$]. The observers identified both target properties faster when two features appeared within the same object (783 msec) than when they appeared in two different objects (878 msec). The main effect of stimulus type was not significant [$F(1,27) = 0.1, p > .8$]. The two-way

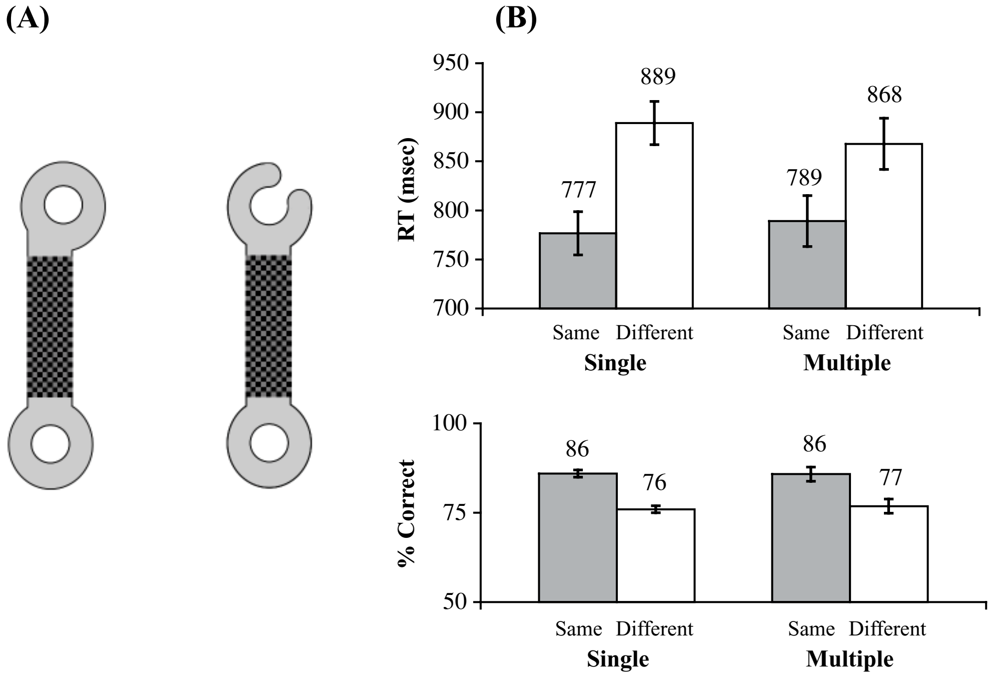

Figure 3. (A) An example of multiple-region stimuli from Experiment 2. (B) Experiment 2: Mean RT (msec) for correct responses (top) and accuracy (percent correct; bottom) on the function of object type and stimulus type.

interaction between object type and stimulus type that we observed in Experiment 1 disappeared [$F(1,27) = 1$, $p > .27$]. As Figure 3B indicates, the observers showed a strong object-based effect in both single- and multiple-region conditions. In other words, the observers' RTs were shorter when two target properties appeared within one wrench than when they appeared in two different wrenches, regardless of whether a wrench body had the handle. The sizes of the object-based effect were 112 msec for the single-region condition and 79 msec for the multiple-region condition. The results suggest that object-based effects resurface when the contours of multiple regions can be successfully grouped into a single perceptual object. Specifically, the presence of the smaller checkerboard pattern results in the appearance of a seamless contour at the edge of the handle. This contour can be readily grouped with the contours of the gray wrench ends, which allows the different regions to cohere into a single perceptual object. Planned pairwise comparisons verified that the difference between the same- and different-object trials was significant for both single-region stimuli [$t(27) = 5$, $p < .0005$] and multiple-region stimuli [$t(27) = 3$, $p < .0005$].

Accuracy followed the same pattern as RT. There was a main effect of object type [$F(1,27) = 35$, $p < .0005$]. However, neither the main effect of stimulus type nor the two-way interaction between object and stimulus types was significant [$F(1,27) = 0.1$, $p > .76$ and $F(1,27) = 0.25$, $p > .62$, respectively].

The present results demonstrated an object-based effect in multiple-region objects. Although the object-based effect was numerically smaller in the multiple-region objects than in the single-region objects, this difference was not significant. It appears that when the texture of the handle pattern was reduced to create the percept of a purple handle, the edge of the handle could perceptually group with the edge of the gray wrench ends. Thus, attention could be directed toward this single perceptual object.

Although the results of Experiment 2 suggest that edge grouping may contribute to the formation of perceptual objects, reducing the size of the checkerboard pattern on the handle was an indirect manipulation of edge grouping. Thus, we decided to manipulate the grouping of the separate regions in a more direct manner—namely, to enclose the entire object with a single black contour. Such a contour allows the different regions to be grouped without changing the size of the checkerboard pattern used in Experiment 1. Thus, we intended to demonstrate that the stimuli with the large checkerboard pattern could cause object-based effects when the contour of the handle could be perceived as collinear with the contour of the wrench ends.

In Experiment 3, we tested whether object-based attention could select multiple-region objects when another contour-grouping cue cohered the regions of our stimuli into a single perceptual object. In Experiment 3, every wrench was surrounded by a black contour. Stimuli in Experiment 3 differed from those in Experiment 1 only in the inclusion of the contour that surrounded the entire object and explicitly grouped the handle and wrench ends. We hypothesized that object-based effects would remain strong for both single- and multiple-region conditions, as observed in Experiment 2. Unlike in Experiment 1, the observers would perform the task faster and more accurately when two target properties appeared within one object than when they appeared in two different objects, regardless of whether the wrench included the handle. In other words, the results of Experiment 3 should show a pattern similar to that observed in Experiment 2. Experiment 3 consisted of two experiments; the only difference between the two experiments was the width of the contour. In Experiment 3A, the contour surrounding the object was thick (5 pixels), whereas in Experiment 3B, the contour was thin (1 pixel). Experiment 3B allowed us to ask whether a relatively small amount of contour information could allow the contours of multiple regions to be grouped.

EXPERIMENT 3

Experiment 3A

Method

Participants. The observers were 28 University of Iowa undergraduates who received either course credit or payment; all were between 18 and 30 years of age and reported having normal or corrected-to-normal vision. None of the observers participated in any of the other experiments reported in the present article.

Stimuli and Procedure. Both the single- and multiple-region stimuli used in Experiment 3A are illustrated in Figure 4A. The width of the black contour was 0.16º (5 pixels). All of the other procedures were identical to those described in Experiment 1.

Results and Discussion

The analyses were conducted in the same manner as in the previous experiments. Trimming RTs over 3 *SD*s above each condition mean removed less than 1.3% of the overall RTs. Mean RTs and accuracies are presented in Figure 4B. For RT, there was a significant main effect of object type [$F(1,27) = 38, p < .0005$]. The observers reported two target properties faster when these features appeared within one wrench (752 msec) rather than in two different wrenches (820 msec). There was no main effect of stimulus type [$F(1,27) = 0.1, p > .8$], indicating that single- and multiple-region objects were responded to similarly. Finally, consistent with the results of Experiment 2, the two-way interaction between object and stimulus types was not significant, although it was marginal [$F(1,27) = 4, p > .07$]. Regardless of whether the handle was embedded between two wrench ends, the observers identified two target properties with shorter RT when these features appeared within one object than when they appeared in two different objects.

Although the interaction between object and stimulus types showed a trend toward significance, the object-based effect size in the multiple-region objects was smaller (53 msec) than in the single-region objects (84 msec). However, the effect size of the multiple-region stimuli in the present experiment (53 msec) was larger than in Experiment 1 (25 msec), suggesting that the addition of a

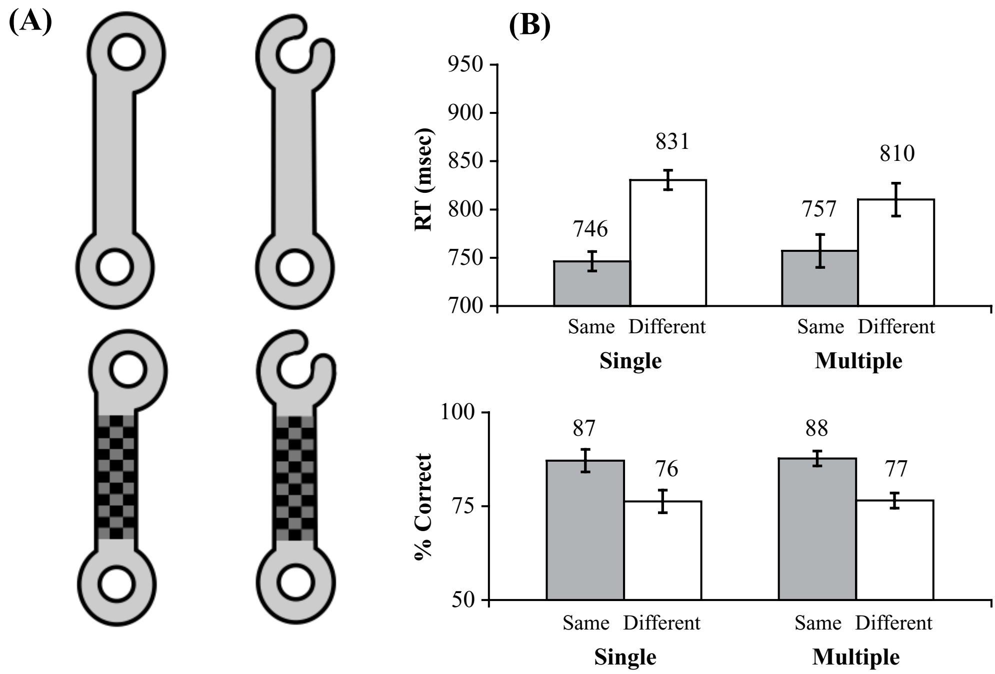

Figure 4. (A) An example of stimuli from Experiment 3A: A single-region wrench pair on the top and a multiple-region wrench pair on the bottom. (B) Experiment 3A: Mean RT (msec) for correct responses (top) and accuracy (percent correct; bottom) on the function of object type and stimulus type.

contour around the object increased the grouping of the regions, thereby producing an object-based effect. Supporting these effect size differences among critical conditions, planned pairwise comparisons revealed that the difference between the same- and different-object trials was significant for both single-region trials [$t(27) = 9$, $p < .0005$] and multiple-region trials [$t(27) = 3$, $p < .0005$].

Accuracy was consistent with the RT data. There was a main effect of object type [$F(1,27) = 26$, $p < .0005$]. However, neither the main effect of stimulus type nor the two-way interaction between object and stimulus types was significant [$F(1,27) = 0.2$, $p > .7$ and $F(1,27) = 0.04$, $p > .9$, respectively].

Having demonstrated object-based effects with multiple-region objects, we next asked how little visual information could be used to group the contours of the regions. In Experiment 3B, the contour width was only 1 pixel, and the only difference between the stimuli in Experiment 1 and those in Experiment 3B was whether or not the side of the handle was outlined by a 1-pixel contour.

Experiment 3B

Method

Participants. The observers were 28 University of Iowa undergraduates who received either course credit or payment; all were between 18 and 30 years of age and reported having normal or corrected-to-normal vision. None of the observers participated in any of the other experiments reported in the present article.

Stimuli and Procedure. The stimuli and procedures were identical to those used in Experiment 3A except that the width of the surrounding contour was reduced from 5 pixels to 1 pixel, 0.03° (Figure 5A).

Results and Discussion

The analyses were identical to those used in the previous experiment. Trimming RTs over 3 *SD*s above each condition mean removed less than 1.7% of the overall RTs. Mean RTs and accuracies are presented in Figure 5B. For the RT data, there was a main effect of object type [$F(1,27) = 15$, $p < .0007$], indicating that observers detected two target properties faster when these features belonged to one wrench (738 msec) rather than to two different wrenches (816 msec). There was no main effect of stimulus type [$F(1,27) = 0.1$, $p > .8$]. Finally, as in Experiments 2 and 3A, the two-way interaction between object and stimulus types disappeared when the entire wrench was surrounded by a contour [$F(1,27) = 2$, $p > .22$]. Planned pairwise comparisons revealed that the difference between the same- and different-object trials was significant for both single-region stimuli [$t(27) = 5$, $p < .0005$] and multiple-region stimuli [$t(27) = 2$, $p < .02$].

Accuracy again mirrored the RT results. There was a main effect of object [$F(1,27) = 23$, $p < .0005$], but neither the main effect of stimulus type nor the two-way interaction between object and stimulus types was significant [$F(1,27) = 1$, $p > .4$ and $F(1,27) = 4$, $p > .06$, respectively]. Although the interaction between these two factors showed a trend toward significance, this interaction was not significant in the accuracy data in Experiment 3A.

The results of Experiment 3B replicated the pattern observed in Experiments 2 and 3A. The observers identified two target properties with a shorter RT when these features appeared within one object rather than in two different objects, regardless of whether the colorful handle was

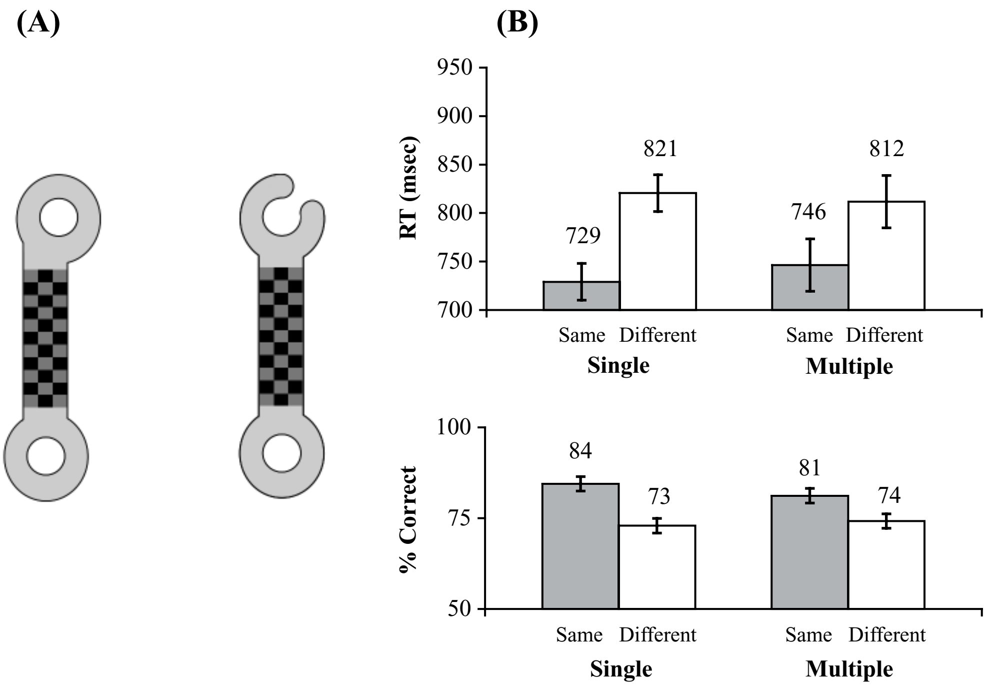

Figure 5. (A) An example of multiple-region stimuli from Experiment 3B. (B) Experiment 3B: Mean RT (msec) for correct responses (top) and accuracy (percent correct; bottom) on the function of object type and stimulus type.

embedded between the two wrench ends. The size of the object-based effect became larger even for trials in which objects were composed of multiple regions with different color and textures, when an appropriate perceptual grouping cue was available. Even 1 pixel of contour was able to encourage observers to perceive the wrench with multiple regions as a single object. Importantly, the present interaction was not marginal, as it was in Experiment 3A. The marginal interaction between object and stimulus types observed in Experiment 3A was likely due to a near Type I error.

One could find the present result rather puzzling, because the sole difference between Experiments 1 and 3B was a single-pixel-wide contour that included the edge of the handle.

Consistent with Watson and Kramer's (1999) Experiment 2, we suspect that the Experiment 3B result was partially affected by observers' prior experience with multiple-region wrenches. The observers in Experiment 3 were told that every wrench was surrounded by a contour, and they were shown grayscale pictures of the stimuli when they received the instruction. As we discussed in the introduction, Watson and Kramer found that top-down task-relevant factors allowed their observers to group the handle with the wrench ends in the absence of a small amount of perceptual information (i.e., a contour that surrounded the objects, as in our studies). We speculate that the observers' knowledge of contour existence may have contributed to the object-based effects observed on the multiple-region objects in the present experiment. However, as a critical difference, our displays had perceptual information, the surrounding contour, that supported this interpretation of the displays.

Thus far, we have examined the effect of direct contour-grouping cues on the size of object-based attention when objects are composed of multiple regions. Experiments 2 and 3 demonstrated that object-based selection operated when different regions could successfully cohere into a single perceptual object.

Given that the observed object-based effects from the present paradigm were subtle and that there were few inconsistencies in Experiment 3 data, we decided to pool Experiments 2, 3A, and 3B into a single analysis. Ivanoff, Klein, & Lupiáñez (2002) used a similar procedure to demonstrate a significant interaction between inhibition of return (IOR) and the Simon effect. Although each single experiment did not show a statistical interaction, their pooled analysis did exhibit a theoretically relevant statistical interaction. Taking the same approach, we pooled our three edge-continuation experiments to see if there was a significant interaction between object and stimulus types. If this pooled analysis showed a significant two-way interaction, the result should be interpreted as the difference between the "poor edge continuity" experiment (Experiment 1) and the "good edge continuity" experiments (Experiments 2, 3A, and 3B), and reflect a graded nature of object-based selection rather than an all-or-none effect. In fact, there was a significant main effect of object type [$F(1,83) = 9, p < .0005$], indicating that the observers detected two target properties faster when these features belonged to one wrench (757 msec) rather than to two different wrenches (838 msec). There was no main effect of stimulus type [$F(1,83) = 0.03, p < .9$]. Finally, the two-way interaction between object and stimulus types was significant [$F(1,83) = 5, p < .02$]. The object-based effect size in the multiple-region objects was smaller (66 msec) than in the single-region objects (96 msec), although this two-way interaction was not significant in the analyses of the individual experiments. These results indicate that the differences between Experiment 1 and each of the edge-continuation experiments reflect a matter of degree in object-based selection, rather than being absolute. Specifically, although object-based attention can select multiple-region objects when provided with the appropriate grouping cues, object-based effects for these multiple-region stimuli remain smaller than those for single-region objects.

In the final experiment, having demonstrated the role of edge grouping on selection of multiple-region objects, we examined another grouping cue that could allow object effects to emerge in multiple-region objects. Previous findings have demonstrated object-based effects within occluded objects (Behrmann et al., 1998; Moore et al., 1998; Pratt & Sekuler, 2001). As discussed in the introduction, occlusion creates a situation in which the projection of an object is composed of multiple regions (i.e., the visible ends of the objects plus the occluder). We have demonstrated that encouraging grouping among multiple-region objects allows object-based effects to be observed. Do our multiple-region objects exhibit object-based effects when perceptual information entices the different regions to be perceived as separate objects, one occluding the other? In Experiment 4, we made one minor modification to the multiple-region stimuli used in Experiment 1. We increased the width of the handle, which created a concave cusp at the intersection between the wrench ends and the handle. Such cusps are reliable cues for predicting the boundaries of parts of an object (Hoffman & Richards, 1984; Hoffman & Singh, 1997), or, alternatively, for perceiving objects that extended behind the occluder (Behrmann et al., 1998; Moore et al., 1998; Pratt & Sekuler, 2001).

Although these modified wrenches consist of regions of different color and luminance, the addition of concave cusps should encourage these different regions to segregate into separate parts or surfaces. Consequently, the wrench ends should be grouped with one another behind the handle, and object-based effects should be observed. Such results would link studies of occlusion in object-based attention (Behrmann et al., 1998; Moore et al., 1998; Pratt & Sekuler, 2001) with our results that demonstrate object-based attention for multiple-region objects.

We should note that Watson and Kramer (1999) demonstrated that the magnitude of concave discontinuity of wrenches affected the size of the object-based effect of attention. The effect size of object-based attention increased as the magnitude of the concave cusps at which the wrench ends were connected to the shafts decreased. One crucial difference between our Experiment 4 and Watson and

Kramer's Experiment 3 was that we increased concave discontinuity on an object's surface structure (i.e., the extended width of the handle) but not an object's geometrical structure (i.e., concavities of the wrench body itself). Consequently, our manipulation provided both part and occlusion cues to an object, whereas Watson and Kramer's manipulation assigned only a part-boundary cue. We were interested in whether object-based attention would select occluded wrench bodies as a unitary percept when these bodies were grouped separately from the handle region.

EXPERIMENT 4

The observers performed the target search task as in the previous experiments. However, the wrench handles were now widened to include concave cusps at the intersection of the wrench ends and handles, as shown in Figure 6A. These concave cusps distinguish both part boundaries and occluded/occluding regions. The presence of either part boundaries or occlusion allows the wrench ends to be more readily grouped with one another, and to be grouped separately from the handle region. Consequently, the presence of these cusps should permit object-based attention to select the wrenches as a single object behind the occluding handle.

Method

Participants. The observers were 28 University of Iowa undergraduates who received either course credit or payment; all were between 18 and 30 years of age and reported having normal or corrected-to-normal vision. None of the observers participated in any of the other experiments reported in the present article.

Stimuli. Multiple-region stimuli used in Experiment 4 are illustrated in Figure 6A. The computer system, stimuli, and procedures were identical to those used in the previous experiments, except that the width of the handle was increased and the height was decreased.

The size of each checkerboard square was identical to those used in Experiment 1. In the present experiment, four rows of checkerboard squares were removed from the handle's height and three columns of squares were added to its width (i.e., one and a half columns of squares were extended to both sides). Consequently, the handle was transformed into a 6×6 checkerboard. The handle's area in Experiment 4 contained 36 checkerboard squares, whereas it contained 30 checkerboard squares in Experiment 1. As a result of this modification, more area of the gray wrench was exposed on the display than in Experiment 1. At the specified viewing distance, the handle subtended 3.4º to each side, whereas all of the measurements of a pair of gray wrenches remained the same.

Results and Discussion

The analyses were identical to those used in the previous experiments. Trimming RTs that were over 3 *SD*s above each condition mean removed less than 1.2% of the overall RTs. Mean RTs and accuracies are presented in Figure 6B. For the RT data, there was a main effect of object type [$F(1,27) = 29, p < .0001$], indicating that the observers detected two target properties faster when these features belonged to one wrench (760 msec) rather than to two different wrenches (819 msec). There was no main effect of stimulus type [$F(1,27) = 0.1, p > .3$]. Finally, the two-way interaction between object and stimulus type was significant [$F(1,27) = 5, p < .04$], suggesting that

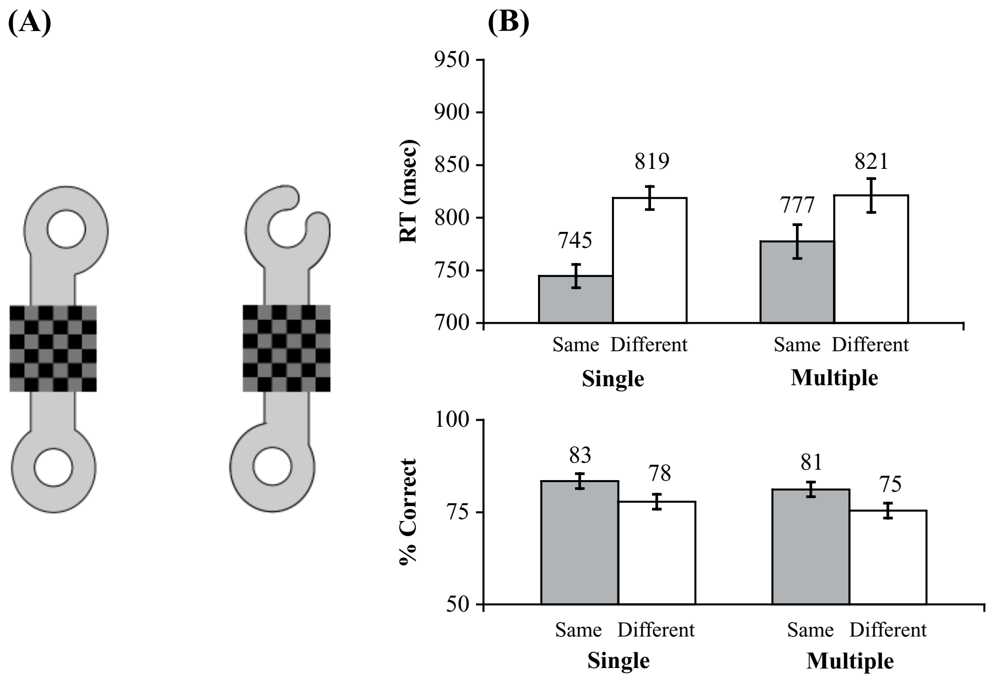

Figure 6. (A) An example of multiple-region stimuli from Experiment 4. (B) Experiment 4: Mean RT (msec) for correct responses (top) and accuracy (percent correct; bottom) on the function of object type and stimulus type.

the object-based effect was smaller in the multiple-region condition than in the single-region condition. Importantly, however, the observers identified two target properties with a shorter RT when these features appeared within one object than when they appeared in two different objects, regardless of whether the colorful handle was occluding the wrench body. The object-based effect size in the multiple-region objects was smaller (44 msec) than in the single-region objects (74 msec). Further, the effect size of the multiple-region stimuli in the present experiment (44 msec) was larger than in Experiment 1 (25 msec). A possible reason for these results was that the concave cusp cues used in the present experiment were not as robust as the explicit grouping cues, such as an outlining contour. However, supporting these effect size differences among the critical conditions, planned pairwise comparisons revealed that the difference between the same- and different-object trials was significant for both single-region trials [$t(27) = 7, p < .0005$] and multiple-region trials [$t(27) = 3, p < .008$.]

Accuracy rates were consistent with the RT data. There was a main effect of object type [$F(1,27) = 10, p < .003$]. However, neither the main effect of stimulus type nor the two-way interaction between object and stimulus type was significant [$F(1,27) = 4, p > .07$ and $F(1,27) = 0, p > .9$, respectively].

The present results indicate that object-based selection returns when cusp cues (i.e., minima of curvature cues) are available for observers to perceive the wrench ends as a single surface behind the handle. Although the object-based effect is significantly smaller in the multiple-region objects than in the single-region objects, the object-based effect is significant in the multiple-region objects, unlike what we observed in Experiment 1 and what was reported by Watson and Kramer (1999).

GENERAL DISCUSSION

In five experiments, we have demonstrated that object-based attention can extend to multiple-region objects when the different regions are successfully grouped into a single perceptual object (Experiments 2 and 3) and when the multiple regions are perceived as different parts or as occluding/occluded surfaces (Experiment 4). These results extend Watson and Kramer's (1999) findings, which demonstrated that multiple-region objects would not induce object-based attention in some situations. The present findings are theoretically important for several reasons. First, our results suggest that object-based attention would be likely to operate on many real-world objects that are composed of multiple regions. Second, our findings have identified some of the perceptual information that allows multiple regions of an object to group into a single perceptual object. Third, the results of Experiment 4 bridge studies of occluded objects and multiple-region objects by demonstrating that multiple-region stimuli containing minima of curvature (i.e., concave cusps) exhibit object-based effects. Thus, object-based effects can be observed in multiple regions when those regions group together (Experiments 2 and 3) and when those regions are segregated from one another (Experiment 4).

What is the source of the object-based effects we have observed in our multiple-region objects? Are these effects due to top-down expectancies (e.g., observers' expectation or strategy-produced object-based effects) or to bottom-up image features? As we discussed in the introduction, Watson and Kramer (1999, Experiment 2) reported that object-based effects were observed for multiple-region objects when all of these regions were task relevant or when multiple regions had been primed as a unitary percept. We consider it unlikely that the results of our Experiment 2 were caused by top-down effects, because the observers exhibited clear object-based effects in the absence of any task relevance of the handle. Observers did not have to attend to handle parts to complete the target search task. However, the results of Experiments 3A and 3B could be partially influenced by top-down factors. The observers saw the outline contour, which included the handle, when they read the instructions for the experiments. However, because no explicit instruction to perceive multiple-region objects as "unitary" objects was provided, the colored handle was not task relevant. We would argue that the majority of the effects we have reported are due to image-based (bottom-up) cues contained in the display (e.g., contour grouping in Experiments 2 and 3). Even though our general theoretical position is that top-down effects contribute to the performance of many tasks (e.g., task dependency; see Vecera & Farah, 1994), the present results can be accounted for by image-based cues. Top-down influences are present for both object perception and object-based attention; however, these influences may not need to be invoked to explain the present results.

Watson and Kramer (1999) suggested that, consistent with Palmer and Rock's (1994) theory of perceptual organization, only uniformly connected objects would be selected by object-based attention, because attention had to visit a uniformly connected surface first. Our results do not appear to support uniform connectedness as a default selection unit of object-based attention. Addition of appropriate grouping cues to multiple-region objects facilitated multiple regions to cohere into a single perceptual object, and resulted in the return of object-based effects (Experiments 2 and 3). How can we reconcile our results with Palmer and Rock's conceptualization of uniform connectedness?

One possible answer is that uniform connectedness may be modified by the presence of other perceptual cues, such as the contour grouping or concave cusps in our experiments. Additional cues could override the influence of uniform connectedness at later processing stages, after the initial influences of uniform connectedness as an entry-level grouping cue. Alternatively, other cues could influence an early uniform connectedness process in a top-down manner. Our results do not distinguish these alternatives, although they do suggest that uniform connectedness may not be a necessary constraint on visual perception. In other words, uniform connectedness is one of many perceptual cues that contribute to object-based attention. Future research would be necessary to determine the relative strength of the various grouping cues that influence object-based attention.

In line with the data presented above, we view the present results as continuing to demonstrate a role for uniform connectedness, as in Watson and Kramer's (1999) studies. However, as suggested by a comparison across our experiments, uniform connectedness does not always cause object-based effects to disappear. For the three experiments with edge-continuation cues, we found a reduced size of the object-based effect for multiple-region objects in comparison with single-region objects. Object-based effects were larger for multiple-region objects that contained cues that supported grouping the regions into a single perceptual object (66 msec in Experiments 2 and 3) than they were for objects that lacked these cues (25 msec in Experiment 1). This difference between the RT of the "poor edge continuity" experiment (Experiment 1) and the collapsed RT over the "good edge continuity" experiments (Experiments 2 and 3) showed a trend toward significance [$F(1,54) = 4$, $p < .08$]. The difference between the RT in Experiment 1 (25 msec) and the average RT of all the perceptually grouped experiments (Experiments 1–4, 60 msec) also showed a strong trend [$F(1,54) = 3$, $p < .10$]. On the basis of these observations, it is clear that, with appropriate perceptual cues, reliable object-based effects can be observed for multiple-region objects, and the magnitude of the object-based effect can be modulated on the basis of the strength of the cues that group multiple regions. Thus, the selection of multiple-region objects seems to be a graded rather than an all-or-none phenomenon. Other grouping cues can allow object-based effects to appear in multiple-region objects, but these object effects are not as large as those in single-region objects.

We should note that studies that have investigated object-based effects in occluded versus nonoccluded objects (Behrmann et al., 1998; Moore et al., 1998; Pratt & Sekuler, 2001) found object-based effects that were similar in size. An understanding of the conditions that will reduce object-based effects will require an understanding of the various perceptual cues to which object-based attention is sensitive. Presumably, strong grouping cues would increase the size of the object-based effect for multiple-region objects, whereas weaker grouping cues might allow object-based effects to be reduced in multiple-region objects. For example, with an implicit measure, Reppa and Leek (2003) reported that object-based IOR was attenuated when the cue and the target appeared on the same part of an object in comparison with when the cue and the targets appeared on different parts of an object. This issue seems ripe for future research and could serve to integrate object-based attention with a large literature on the combination of perceptual cues.

Our results raise more general issues about the operation of object-based attention that have not been addressed fully in the literature. These issues include the question: What role does a "part" play in an object's structure? For instance, most objects in natural scenes are composed of multiple regions, and these regions typically occur at part boundaries. The results from our Experiment 4 suggest that object-based effects can be observed when regions coincide with potential part boundaries. However, would such effects disappear if region information did not coincide with part boundaries? Beyond such questions, it is clear that object-based attention can operate when multiple-region groups cohere into a single perceptual object. The flexibility and range of object-based selection depends on how successful grouping between multiple regions is achieved.

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NOTE

1. However, previous experience with multiple-region real-world objects might allow these regions to be grouped together and produce object-based effects. Thanks to Art Kramer for pointing this out.

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