How Object-Specific Are Object Files? Evidence for Integration by Location

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Given the distributed representation of visual features in the human brain, binding mechanisms are necessary to integrate visual information about the same perceptual event. It has been assumed that feature codes are bound into object files—pointers to the neural codes of the features of a given event. The present study investigated the perceptual criteria underlying integration into an object file. Previous studies confounded the sharing of spatial location with belongingness to the same perceptual object, 2 factors we tried to disentangle. Our findings suggest that orientation and color features appearing in a task-irrelevant preview display were integrated irrespective of whether they appeared as part of the same object or of different objects (e.g., 1 stationary and the other moving continuously, or a banana in a particular orientation overlaying an apple of a particular color). In contrast, integration was markedly reduced when the 2 objects were separated in space. Taken together, these findings suggest that spatial overlap of visual features is a sufficient criterion for integrating them into the same object file.

Keywords: feature integration, attention, binding

Visual information processing occurs in a distributed fashion—different features of a visual object are processed in spatially and functionally distinct cortical areas (Zeki, 1976). Given that event representations depend on distributed neural codes, a mechanism needs to be in place that integrates the codes representing the perceptual (Treisman, 1996) and response features (Stoet & Hommel, 1999; Wickens, Hyland, & Anson, 1994) of an event. Kahneman, Treisman, and Gibbs (1992) suggested that encountering a particular combination of visual features leads to the creation of what they call an *object file*—a cognitive structure that cross-references all the features belonging to a particular object (cf. Allport, Tipper, & Chmiel, 1985). They reasoned that binding features into an object file may produce specific aftereffects that benefit performance if this particular combination is repeated. They presented participants with visual arrays of randomly arranged letters in constantly visible boxes (the preview display or *prime*) followed by the presentation of a to-be-named target letter in one of the boxes (the *probe*). Two types of effects were observed: Performance was better if the probe letter had already

appeared in the preview display than if it had not, but it was particularly good if the letter had appeared in the same box. Hence, there was both a nonspecific identity-priming effect (a benefit due to shape or letter repetition) and what Kahneman et al. called an *object-specific preview benefit* (a benefit due to the repetition of both shape and location).

Kahneman et al. (1992) interpreted object-specific preview effects as benefits resulting from the fact that repeating a feature combination (a shape and a location in their case) allows the receiver to make use of an already existing object file that already contains this particular combination. That is, if the probe matches the prime, it can in a sense take over and reuse the object file that was created to represent the prime. However, Hommel (1998) suggested an interpretation in terms of partial-overlap costs: Repeating one or more features may lead to the automatic retrieval of the just created episodic binding, which creates code confusion if the retrieved feature codes do not entirely match with the features of the present stimulus–response episode. In the Kahneman et al. study, only three cells of what one may consider a two-by-two design were investigated: the repetition of letter identity and location, the repetition of letter identity only, and the alternation of both identity and location.[1] In contrast, Hommel's design, which differed mainly in presenting only one prime stimulus at a time, allowed looking into all four combinations of identity and location repetition and alternation and to dissociate the effects of several nonspatial features. It turned out that repeating the combination of two features, such as a particular shape and a location or a particular shape and a color, yields no better performance than if both shape and location or shape and color were changed. Instead, performance is hampered if some but not all features repeat.

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[1] Following common practice in research on repetition effects, we use the term *alternation* as an antonym of *repetition* to refer to change (of features, stimuli, or responses) as such but not necessarily regular changes.

Along the lines of Kahneman et al. (1992), this suggests that codes of co-occurring features are spontaneously bound, and that repeating at least one feature leads to the retrieval of the whole binding. This retrieval may or may not facilitate the processing of the present stimulus if all features repeat (an issue we get back to below) but in any case may create code confusion in the case of only partial repetitions (Hommel, 2004). Assume, for instance, a red or green X or O (the prime) is followed by a red O (the probe). In case of a partial repetition (if the prime was a red X or a green O), retrieving the prime's object file would reactivate the previously bound, no longer valid fellow code (the X code and the *green* code, respectively), which should interfere with processing the present shape and color, respectively. This interpretation is supported by the recent functional MRI study of Keizer, Nieuwenhuis, Colzato, Theeuwisse, Rombouts, and Hommel (2008). Participants responded to the direction in which a target stimulus moved, after having ignored an also moving prime. Primes and probes consisted of overlaid pictures of faces and houses, with either the face or the house moving in one or another direction (see O'Craven, Downing, & Kanwisher, 1999). Encountering a moving face led to a significant increase of activation in the parahippocampal place area (which is known to encode pictures of houses) if the preceding prime showed a house moving in the same direction, suggesting that repeating the motion led to an automatic retrieval of the apparently bound house features. Moreover, individual differences in the size of the reactivation effect in the parahippocampal place area showed a positive correlation with the corresponding partial-repetition costs in reaction times, suggesting that these costs might indeed be due to retrieval-induced code conflict.

Whereas the negative role of code conflict seems to be relatively well understood, it is less clear whether complete repetitions actually play the positive role that Kahneman et al. (1992) had envisioned. At least two scenarios can be conceived of to account for the available data. According to one, object files from previous trials only come into play if at least one feature is repeated. The fact that "complete" alternations (if, in our example, the prime was a green X) commonly yield performance that, if anything, is no worse than complete repetitions (with a red O as a prime; e.g., Hommel, 1998) might suggest that object-file retrieval can induce competition only (with partial repetitions) but no facilitation (with complete repetitions). For instance, it might be that reactivated object files cannot simply be "taken over" to code the present stimulus (as Kahneman et al. had assumed to explain object permanence) or always induce some degree of competition with the presently created object file (cf. Desimone & Duncan, 1995). Accordingly, both complete repetitions and alternations might provide a kind of neutral baseline, so that repetition effects mainly reflect processing costs due to object-file retrieval. According to the other scenario, both complete repetitions and alternations might facilitate probe processing beyond just not creating code conflict (Dutzi & Hommel, 2009). This option is based on the integrated competition hypothesis suggested by Duncan and colleagues (Duncan, 1996; Duncan, Humphreys, & Ward, 1997). They share the view of Kahneman et al. that codes of stimulus events are integrated into object-file type cognitive structures. One consequence of being integrated into such an event structure, so they assume, is that the integrated members benefit from competitive gains achieved by their fellow members, so that integrating X and *red* when processing the prime has the consequence that

increasing the activation of the X code when processing the probe also supports the *red* code in its competition with other color-related codes, and that activation of the *red* code supports the X code in its competition with other shape codes. The flipside of integrated competition is that losses in the competition also spread among members, so that outcompeting the O code when facing a red X probe after a green O prime will also weaken the bound *green* code. In other words, integrated elements win together and lose together. This would suggest that both complete repetitions and alternations produce (probably comparable) benefits, which would fit with idea of Kahneman et al. that complete repetitions facilitate performance. Which of these versions will eventually turn out to be correct was less important for the present study than the shared assumption that differences between complete repetitions and alternations on the one hand and of partial repetitions on the other (differences that we, for the sake of convenience, still refer to as *partial-repetition costs*) reflect the integration of perceptual features.

Kahneman et al. (1992) and numerous studies that followed (e.g., Gordon & Irwin, 1996; Henderson & Anes, 1994; Mitroff, Scholl, & Noles, 2007; Noles, Scholl, & Mitroff, 2005) were focusing on when and under what circumstances previously created object files are *retrieved*—the process that Kahneman et al. called *object reviewing*. For instance, Kahneman et al. (e.g., Experiment 5) used their basic setup consisting of a preview display with, for instance, four letters presented in constantly visible boxes, followed by a probe letter appearing in one of the boxes. However, after the prime letters had disappeared and before the probe letter was presented, the boxes were rotated around the screen center. As before, the probe letter was responded to faster if it was presented in the same box as in the preview display, even though this box no longer occupied the same physical location. This rules out an account of the review effect in terms of low-level (e.g., retinotopic) feature priming and confirms that it reflects the integration and later retrieval of object-related information. Kahneman et al. suggested that encountering the preview display led to an integration of letter identities and boxes into object-specific representations, which were updated when the objects/boxes moved and retrieved when the letter reappeared, leading to a facilitation of performance if the same letter appeared in the same box.

Even though these and numerous other observations provide strong support for the existence of episodic object files, little is known about how and according to which criteria object files are *created* in the first place. Kahneman et al. (1992, p. 178) merely took for granted "that the visual field is parsed into perceptual objects and a relatively undifferentiated perceptual ground" and that not further specified perceptual processes extract the object-related feature information and bind them into corresponding object files. How and according to which criteria this information is selected for inclusion in a particular object file, and whether or how this selection can be controlled in a top-down fashion remained unclear in the original approach (see below for later extensions). In the following, we briefly review the available evidence on two selection criteria—task relevance and time—before we turn to a pair of alternative criteria that the present study was focusing on: location versus objecthood.

With respect to the control and attentional requirements of integration, the available evidence points to a high degree of

automaticity of object-file creation. Features are bound to each other even if the binding itself is unnecessary and the features involved therein are entirely irrelevant to the task at hand (Hommel, 1998; Hommel & Colzato, 2004). Moreover, the probability and strength of binding is unaffected by distraction and extra attentional demands (Hommel, 2005). However, review effects have been observed to be more pronounced and robust with real-life stimuli like pictures of fruit, houses, and faces than with simple features like oriented lines or geometric shapes (Colzato, Raffone, & Hommel, 2006; Hommel & Colzato, 2009). This suggests that the match between a given stimulus and object-specific long-term memory traces provides attentional top-down support for the features of that stimulus, which increases the probability that these features are being integrated (Hommel & Colzato, 2009). In any case, people seem to have little or no control over whether they bind feature codes or which features they bind.

With respect to time, there is preliminary evidence that object-file creation makes use of temporal integration windows over which sensory information is collected and integrated, and that people have some control over the width of these windows. Evidence for integration within time windows comes from the observation that visual stimuli appearing in close succession tend to be recalled together but are often confused with respect to their original temporal order (Hommel & Akyürek, 2005; Potter, Staub, & O'Connor, 2002). This seems to suggest that temporally close stimuli are integrated into the same episode or object file, which facilitates common retrieval but eliminates order information (Hommel & Akyürek, 2005). Akyürek, Toffanin, and Hommel (2008) showed that which or how many stimuli are integrated in this fashion depends on the temporal expectations of the individual. They made two groups of participants expect either very fast or very slow trains of visual stimuli, with the assumption that fast trains would induce rather short integration windows (to help segregating the visual events in time) and slow trains rather long integration windows. In line with this idea, the expectation of a slow train increased common recall combined with order confusions (as measured with stimuli presented at the same rate in both groups), suggesting that this expectation indeed led to a wider temporal integration window. Comparable differences were obtained even if the presentation rate was physically identical in the two experimental groups but only appeared to be faster or slower. This confirms that it must be top-down factors that are responsible.

An event-related potential study of Akyürek, Riddell, Toffanin, and Hommel (2007) further demonstrated that the expectation of a fast train of stimuli induces separate N2- and P3-type components for each of two successive stimuli, whereas the expectation of a slow train induces only one single N2- and P3-type component for both stimuli. Even though these observations relate to the integration of stimuli but not stimulus features, they can be taken to suggest that integration processes use integration windows with an adaptive, task-specific temporal width.

There is thus preliminary evidence on the role of temporal coincidence in the integration of features into object files, but the function of spatial aspects remains unclear. On the one hand, for a long time location has been claimed to play a crucial role in feature integration (e.g., Treisman & Gelade, 1980), and numerous findings from all sorts of attentional tasks are consistent with this assumption. Even though criteria for integration were not dis-

cussed by Kahneman et al. (1992), Treisman (e.g., 1992, 1998) has suggested that spatial location may be the main criterion for constructing object files. More specifically, she assumed that all the features falling into the currently attended spatial region are coded and integrated into the same file. On the other hand, however, some authors have doubted whether the role of location is really as central as space-based attentional theories suggest and whether space-related operations precede or follow object-related processes (for overviews, see Mozer & Vecera, 2005; Schneider, 1993; Tipper & Weaver, 1998). For instance, it is not yet clear whether object representations are really created from spatially selective sensory sampling of feature information (implying that location information serves to *create* object representations) or whether spatial selection processes operate on already grouped chunks of object-specific visual information (implying that location information serves to *select* previously created object representations).

In the original review paradigm and the versions that developed since then, location- and object-related contributions to the *creation* of an object file were entirely confounded. Assume, for instance, that a single box would appear at the top center of a screen, the green prime letter *X* briefly appears in the box, the empty box rotates 90° (around the screen center) to the right, and then the green probe letter *X* appears in the box another time. Responding to the letter should be facilitated as compared with, say, a condition in which the prime letter was different, or had a different color, or if the two *X*s appeared in different boxes. This facilitation certainly suggests that information was stored about the relationship between the prime *X*, its color, the box in which it appeared, and the location the box occupied, and that all that information was later retrieved by the presentation of the probe. But what exactly were the criteria for integrating the prime-related information in the first place? In particular, what were the criteria for associating the letter *X* with the color green? Was it because the green color "belonged" to the letter, that is, that it was the letter that was green—as an object account would suggest (see Xu, 2006)? Or was it because the green color and the letter *X* simply occupied the same location or fell into the same attentional spotlight—as a space-based account would suggest?

In an attempt to disentangle and test these two possibilities, we carried out six experiments that compared the roles of location and objecthood for visual feature integration. In the first four of these experiments, we presented two objects with different features at the same location, and tested whether features belonging to two different objects would be integrated to produce partial-repetition costs as reported previously (Hommel, 1998, 2004). The main manipulations between experiments were the ways the two objects were defined and distinguished, such as by shape, motion, etc. Apart from these differences, the stimulus displays always consisted of one larger circular object and one smaller elliptic object, as can be seen in Figure 1. Whereas the circular object varied in color, the ellipse varied in orientation, and the empirical question was whether these two features (the color and the orientation) would be integrated even though they "belong" to two different objects. If they would, they should produce partial-repetition costs, just like features of the same object in previous studies. Assume, for instance, that the combination of a red circle and a horizontal ellipse (appearing as prime) is followed by the combination of a red circle and a vertical ellipse (the probe). If the combination of
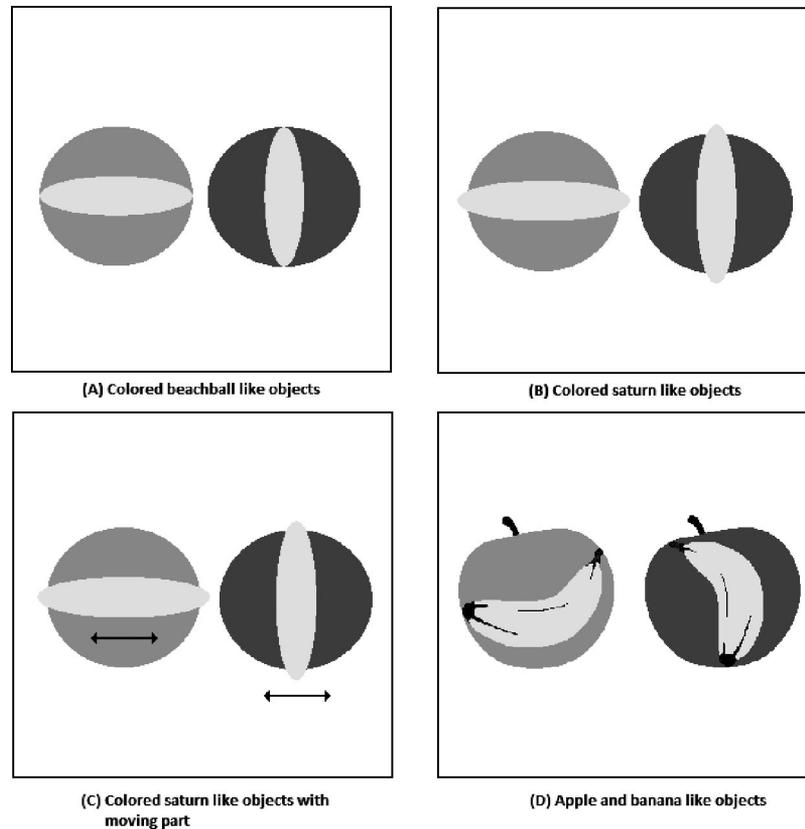
Figure 1. Example of the stimuli used in Experiments 1–4. (A) The ends of the yellow ellipse are in perfect alignment with the contour of the colored circle; (B) the ends of the yellow ellipse do not exactly follow the contour of the colored circle; (C) the chance of interpreting the image as two objects is enhanced by a left-to-right motion of the yellow oriented ellipse, and the partially occluded circle stays motionless; (D) instead of using arbitrary shapes (circle/ellipse), we use objects (apples and bananas), for which subjects likely have long-term memory representations.

red and *horizontal* is integrated into the same object file on prime presentation, subjects should find it difficult to respond to a partially overlapping probe: The repetition of red should retrieve the *horizontal* code, which now conflicts with the actually relevant *vertical* code. The same should be true for the partial repetition of orientation (e.g., green circle and a horizontal ellipse as prime, followed by a red circle and a horizontal ellipse as probe), whereas complete repetitions (e.g., green circle and a horizontal ellipse as prime, followed by a green circle and a horizontal ellipse as probe) and alternations (e.g., red circle and a vertical ellipse as prime, followed by a green circle and a horizontal ellipse as probe) should allow for comparatively good performance.

Experiment 1

The first experiment served the purpose of establishing a single-object baseline. There were two stimuli in each trial, a prime (S1) that did not require any response and the probe (S2) that called for a binary choice reaction. The stimuli were colored (red or green) circles containing a yellow ellipse that was either vertically or horizontally orientated (see Figure 1A). The ends of the yellow ellipse exactly fit the contour of the colored circle. Although the

surface texture of the image allowed for multiple interpretations, we considered a single-object interpretation most likely. The theoretically important features were the color of the circle (henceforth referred to as *color feature*), which was irrelevant to the task, and the orientation of the ellipse (henceforth referred to as *orientation feature*), which signaled the response and was thus task-relevant. Given previous observations with different but similar stimuli varying in task-relevant orientation and task-irrelevant color (e.g., Hommel, 1998), we expected that seeing S1 would lead to the automatic integration of the presented color (of the circle) and orientation (of the ellipse). If so, repeating one of these features on S2 but not the other should hamper performance: The repeated feature would retrieve the previous binding and therefore reactivate its now misleading fellow code (Hommel, 2004). In other words, we expected the usual partial-repetition costs.

Method

Participants. Seventeen students participated; their average age was 24 years. All subjects reported to have normal or corrected-to-normal vision. No subject was aware of the purpose

of the experiment. Prior to their participation, subjects filled in an informed consent.

Apparatus and stimuli.   The experiment was controlled by a Targa Pentium III computer, attached to a Targa TM 1769-A 17-in. monitor. Participants sat at a viewing distance of about 60 cm, the images measured $2.8° \times 3.1°$. The stimuli were red or green circles containing a yellow ellipse with vertical or horizontal orientation (see Figure 1A). The fixation point signaling the advent of S1, S1, and S2 were presented in the center of the screen. Responses to S2 were made by pressing the left or right *shift* key of the computer keyboard with the corresponding index finger.

Procedure and design.   The sequence of events in each trial is shown in Figure 2. Participants saw two stimuli in close temporal succession. The advent of the first stimulus (S1) was signaled by a fixation point (a plus sign appearing for 250 ms) at screen center. After a blank interval of 250 ms, S1 appeared. Participants were instructed to ignore the identity of that stimulus. After an interval of 1,000 ms, S2 was presented, calling for a speeded left–right response to the orientation of the ellipse. The experiment comprised 320 randomly ordered trials composed of 20 replications of the factorial combination of two orientations of the ellipse and the two colors of S2 and the repetition versus alternation of shape and color.

Results and Discussion

After excluding trials in which the reaction times (RTs) deviated more than 1.5 times the interquartile range from the median, we calculated mean RTs for correct trials and error rates as a function of the repetition versus alternation of orientation (horizontal vs. vertical orientation of the yellow ellipse) and color (red or green color of the circle). The significance criterion for all analyses was set to $p < .05$.

A two-by-two repeated measures analysis of variance (ANOVA) was conducted on the RTs for S2. Whereas the (theoretically less interesting) main effects of orientation and color repetition failed to reach significance, $F(1, 16) = 2.88$, $p > .1$, $MSE = 409.68$, $\eta_p^2 = .152$, and, $F(1, 16) = 0.51$, $p > .4$, $MSE = 53.67$, $\eta_p^2 = .031$, the interaction effect was reliable, $F(1, 16) = 21.37$, $p < .001$, $MSE = 87.99$, $\eta_p^2 = .572$. The pattern of this interaction was as expected: Repeating color but not orientation, or vice versa, impaired performance as compared with complete repetitions or alternations (see Table 1). The analysis of the error rates did not reveal any significant outcome.

The outcome is clear: Reliable partial-repetition costs were obtained because repeating orientation but not color, or vice versa, impaired performance as compared with complete repetitions or alternations. This suggests that the combination of orientation and color presented in S1 induced a binding of the corresponding feature codes, which was retrieved on the repetition of one or more of these features in S2. We can thus conclude that the previous observations of spontaneous integration of orientation and color (Hommel, 1998; Hommel & Colzato, 2004) can be replicated with the present stimulus set. Given that these two features actually belonged to different parts of the stimulus, this is a modest but nontrivial extension of previous observations. However, as these two parts still belonged to the same stimulus, the outcome of Experiment 1 does not yet speak to the role of location and objecthood in the creation of object files. The aim of Experiments 2–4 therefore was to systematically increase the phenomenal distinction between the circle and the ellipse, that is, to create two truly distinct objects.

Experiment 2

The aim of the second experiment was to see whether orientation and color would still be integrated if they belonged to phenomenologically different objects. Our first step to create two different objects was to lengthen the main axis of the ellipse so that it no longer fit into the previously surrounding circle (see Figure 1B).

Method

Twenty new students participated; they fulfilled the same criteria as in Experiment 1. The average age was 23.1 years. The method was exactly as in Experiment 1 with one exception: The main axis of the yellow ellipse was 0.5 cm longer than the intersection of the circle.

Results and Discussion

The data were treated as in Experiment 1. The ANOVA of the RTs did not yield any main effect but a significant interaction effect, $F(1, 19) = 10.04$, $p < .01$, $MSE = 88.29$, $\eta_p^2 = .346$, which indicated that partial repetitions impaired performance. For error rates, only a main effect of orientation repetition was obtained, $F(1, 19) = 5.48$, $p < .05$, $MSE = 6.29$, $\eta_p^2 = .224$, indicating that fewer errors were made if orientation was repeated than alternated.
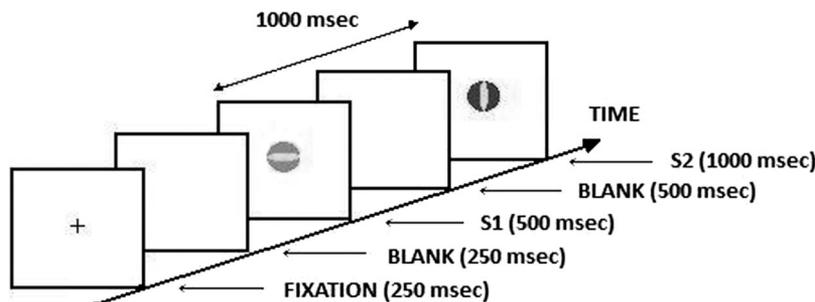

Figure 2.   Overview of the display and the timing of events in Experiments 1–6.

Table 1
Mean Reaction Times (RTs) and Mean Percentages of Error (PE) as a Function of Experiment and Feature Overlap Between Prime and Probe

	Experiment													
	1		2		3		4		5		6 (same)		6 (diff)	
Repeated feature	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE
Neither	396	6.2	405	5.0	424	4.7	391	4.3	339	4.9	390	4.2	400	3.9
Color	405	5.7	411	6.4	428	4.9	397	5.9	344	7.5	403	5.1	399	3.2
Orientation	415	6.1	414	4.5	429	5.2	385	4.6	347	5.3	408	6.1	403	3.5
Both	403	5.1	406	4.3	414	3.1	374	3.2	346	4.7	401	4.5	403	4.7
Partial-repetition cost	11[a]	0.3	7[a]	0.8	9[a]	1.2	8[a]	1.5	3	1.6[a]	10[a]	1.3	−0.5	−1.0

[a] Partial repetition (mean of color repeated and orientation repeated minus mean of neither and both repeated) with significant costs (= reliable interaction of color and orientation repetition).

(Note that main effects are likely to reflect mere priming and thus do not speak to the integration of features; see Kahneman et al., 1992.) Clearly, our attempt to make the two objects more distinguishable did not suffice to eliminate partial-repetition costs, suggesting that integration did not heed object borders.

Experiment 3

Modifying the stimulus material as we did in Experiment 2 was insufficient to eliminate integration of color and orientation, even though these features now belonged to two visibly different objects. However, one may consider this modification marginal and ask whether more drastic modifications may be more effective. In Experiment 3, we chose a more drastic modification by using the two objects of Experiment 2 and having the yellow ellipse moving continuously (see Figure 1C).

Method

Twenty-one new students participated; they fulfilled the same criteria as in Experiment 1. Two participants were excluded from the study: One participant performed below chance level and another failed to complete the experiment. The average age of the remaining 19 participants was 24.4 years. The method was exactly as in Experiment 2 with one exception: The yellow ellipse moved continuously from left to right (extending about 1.3 cm in either direction from the central position) with a speed of 5.2 cm/s. That is, the ellipse traveled 2.6 cm during the 500 ms that the first stimulus (S1) was presented.

Results and Discussion

The RTs ANOVA revealed a main effect of color repetition, $F(1, 18) = 7.18$, $p < .05$, $MSE = 74.77$, $\eta_p^2 = .285$, which was modified by a significant interaction, $F(1, 18) = 15.22$, $p < .005$, $MSE = 111.80$, $\eta_p^2 = .458$, indicating partial-repetition costs (see Table 1). The ANOVA of the error rates only yielded a main effect of color repetition, $F(1, 18) = 5.15$, $p < .05$, $MSE = 3.36$, $\eta_p^2 = .222$, indicating that repeating color reduced the error rates. Further increasing the distinction between the two objects by introducing motion did not eliminate partial-repetition costs. In fact, these costs were not even numerically reduced in comparison with Experiment 2.

Experiment 4

The outcome of Experiment 3 suggests that moving one object but not the other is still insufficient to eliminate cross-object color–orientation integration. However, given that we used arbitrary geometric objects, it is difficult to rule out the possibility that participants somehow coded the whole stimulus as one dynamic event. To exclude this possibility, we used cartoon pictures of real objects in Experiment 4: The yellow ellipse was transformed into a yellow banana and the circle into a red or green apple (see Figure 1D). This should make the two objects easily distinguishable, ascertaining that the red or green color and the orientation of the yellow object would be perceived as belonging to two different objects.

Method

Seventeen new students participated; they fulfilled the same criteria as in Experiment 1. The average age was 23.2 years. The method was exactly as in Experiment 1, except for the mentioned transformation of the circle and the ellipse into an apple and a banana, respectively.

Results and Discussion

The RTs ANOVA yielded a main effect of orientation, $F(1, 16) = 5.64$, $p < .05$, $MSE = 649.64$, $\eta_p^2 = .261$, which was modified by a significant interaction, $F(1, 16) = 20.29$, $p < .001$, $MSE = 52.30$, $\eta_p^2 = .559$, which indicated reliable partial-repetition costs. The error rate ANOVA did not produce any reliable effects, even though the orientation main effect, $F(1, 16) = 3.89$, $p > .05$, $MSE = 6.84$, $\eta_p^2 = .195$, and the interaction, $F(1, 16) = 2.93$, $p > .1$, $MSE = 12.55$, $\eta_p^2 = .155$, approached significance. Further increasing the distinction between the two objects and replacing the geometric shapes by (pictures of) real objects did not have any impact on the presence or size of partial-repetition costs.

Experiment 5

Taken altogether, Experiments 1–4 suggest that the integration of orientation and color does not depend on, and does not consider, whether the two features come from the same object or from two

different objects. Not only did the crucial interaction between orientation and color repetition turn out to be significant in all four experiments, there was also no evidence that the size of the effect differed: An ANOVA on the RTs from all four experiments, with orientation and color as within-participants factors and experiment as the between-participants factor, did not reveal even a hint of a three-way interaction, $F(1, 69) = 0.62$, $p > .6$. This means that object cues are unlikely to be relevant for the integration of visual features, which by exclusion would point to location as the only relevant determinant. To provide positive evidence for this conclusion, we replicated Experiment 4 but now separated the two objects in space. Given that these two objects were the only objects that appeared at a time, and given that on S1 presentation both were task-irrelevant anyway, it is at least conceivable that color (of the circle) and orientation (of the elliptical object) would still be integrated. However, if location really is the dominant factor that we suspect it to be, integration should be considerably impaired as compared with the previous experiments, and partial-repetition costs should thus be reduced or even absent.

Method

Eighteen new students participated; they fulfilled the same criteria as in Experiment 1. The average age was 24.4 years. The method was exactly as in Experiment 4, with one exception: The task-relevant object (banana) was always presented in the center of the screen, as in Experiment 4, but the task-irrelevant object (apple) appeared either above or below the banana, leaving a 1-cm gap between the two objects when the task-relevant object was oriented vertically and 1.5–2 cm when the task-relevant object was oriented horizontally (see Figure 3).
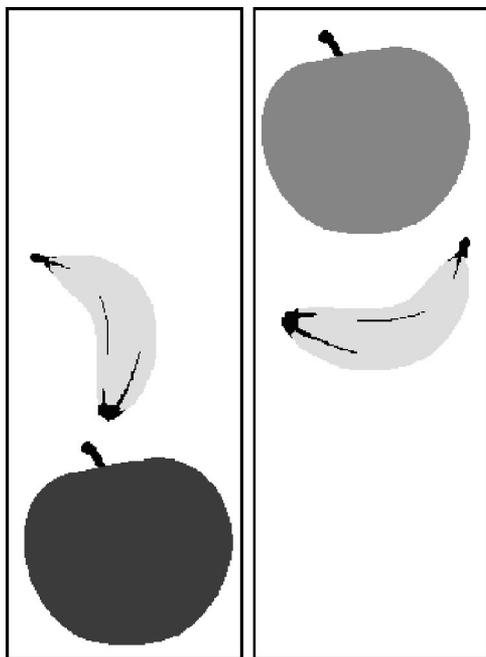

Figure 3. Example of the stimuli used in Experiment 5.

Results and Discussion

The RTs ANOVA did not reveal any reliable effect ($ps > .1$). To test whether the interaction effect differed from that obtained in Experiment 4, we conducted a three-way ANOVA on RTs from Experiments 4 and 5, with orientation and color repetition varying within participants and experiment as the between-participants factor. The three-way interaction was reliable, $F(1, 33) = 5.60$, $p < .05$, $\eta_p^2 = .145$, indicating that the interactions were different in the two experiments. We checked whether this may have been a result of the lower RT level in Experiment 5 as compared with Experiment 4. If we assume that retrieving S1-related episodic traces triggered by the presentation of S2 takes time, fast responses to S2 can be considered to reduce the possibility for retrieved object files to affect performance. To look into that, we Vincentized RTs into quartiles and carried out a three-way ANOVA with orientation, color, and quartile as independent variables. However, no interaction effect came even close to the significance criterion, $F(1, 15) < 2.03$, $p > .1$, suggesting that the impact of orientation and color (and the lack of an interaction between them) did not depend on response speed.

The ANOVA on the error data yielded a marginally significant main effect of orientation, $F(1, 17) = 4.40$, $p = .051$, $MSE = 6.04$, $\eta_p^2 = .206$, that was modified by a significant interaction, $F(1, 17) = 16.70$, $p < .01$, $MSE = 2.63$, $\eta_p^2 = .496$. The size of the interaction effect was almost identical to that obtained in Experiment 4. Indeed, comparing Experiments 4 and 5 did not reveal any hint of a three-way interaction, $F(1, 33) = 0.01$, $p > .50$, suggesting that the orientation by color interaction effect is comparable for Experiments 4 and 5.

On the one hand, the reduction of the costs in RTs is reliable and clearly indicates that separating the object affected feature integration. On the other hand, however, the outcome is not as clearcut as one may have hoped, given that partial-repetition costs disappeared in the RTs but not in the error rates. Hence, even though Experiment 5 does point to a crucial role of stimulus location, the error effect might suggest that our location manipulation failed to eliminate orientation–color binding altogether. Experiment 6 was conducted to see whether this was more than a spurious finding.

Experiment 6

In an attempt to provide more conclusive evidence, we replicated Experiment 4 and Experiment 5 as different conditions within the same experiment. If location is the dominant factor that we suspect it to be, the three-way interaction should show a reliable effect. That is, we expected integration to be considerably impaired (or absent) when the task-irrelevant apple and the banana are separated in space but reliable partial costs when the objects overlap in space.

Method

Twenty new students participated; they fulfilled the same criteria as in Experiment 1. Their average age was 22.7 years. The method was exactly the same as in Experiments 4 and 5, except that the two experiments were transformed into two conditions that varied within subjects. That is, each subject served in one block of trials where the two stimulus objects were presented in the same location, as in

Experiment 4, and another block where the two objects were presented in different locations, as in Experiment 5. The order of the two blocks was balanced across subjects and each block was half as long as in Experiments 4 and 5. Accordingly, Experiment 6 comprised 320 trials composed of 10 replications of the factorial combination of two orientations of the ellipse and the two colors of S2, the repetition versus alternation of shape and color, and the two locations of the two features (same vs. different).

Results and Discussion

RTs and error rates were analyzed by means of three-way ANOVAs with orientation, color repetition, and stimulus location (same vs. different) as within-subjects factors. The RT analysis revealed an interaction between orientation and color, $F(1, 19) = 5.12$, $p < .05$, $MSE = 197.40$, $\eta_p^2 = .212$, which was modified by a significant three-way interaction, $F(1, 19) = 5.71$, $p < .05$, $MSE = 220.63$, $\eta_p^2 = .231$. Separate ANOVAs for the two location conditions yielded a significant interaction between orientation and color repetition for the same-location condition, $F(1, 19) = 8.20$, $p = .01$, $MSE = 276.14$, $\eta_p^2 = .301$, but not any reliable effect for the different-location condition ($ps > .5$). The error analysis yielded a main effect of location, $F(1, 19) = 6.04$, $p < .05$, $MSE = 10.35$, $\eta_p^2 = .232$, indicating more errors in the same-location condition. The three-way interaction failed to reach significance, $p = .066$, but followed the pattern of the RTs: In the same-location condition, errors were more frequent with partial repetitions than with complete repetitions or alternations, whereas in the different-location condition, the error rates tended to show the opposite pattern.

The outcome of Experiment 6 is clear: Reliable partial-repetition costs were obtained in the condition with spatially overlapping objects but not any hint toward integration with spatially separate objects. This replicates our observations from Experiments 4 and 5 and reinforces the consideration that stimulus location is crucial for integration.

General Discussion

The present study made an attempt to disentangle two commonly confounded conditions that may underlie the integration of visual features into object files: shared location (i.e., whether or not two or more given features fall into the same spatial location) versus shared objecthood (i.e., whether or not the features are part of the same object). Experiment 1 replicated earlier findings that repeating versus alternating orientation and color features leads to partial-repetition costs, that is, repeating one feature without the other impairs performance (Hommel, 1998). This suggests that registering a particular conjunction of visual features is sufficient to create a binding between them, even if the task does not require such integration and even if all possible conjunctions are equally probable. The reoccurrence of at least one element of such a binding is sufficient to retrieve the just created binding in a pattern-completion fashion, thus creating feature conflict if other features are not repeated (Hommel, 2004). Experiments 2–4 employed increasingly drastic measures to separate the orientation and color information under investigation to make sure that they are perceived as belonging to two different objects. And yet, partial-repetition costs remained unchanged, suggesting that fea-

ture integration was not affected by these manipulations. Only Experiment 5, where the two objects containing the orientation and color information were separated in space, showed some effect: Partial-repetition costs were no longer significant in the RTs. Experiment 6 replicated Experiments 4 and 5 and provided further evidence for a crucial role of stimulus location in the integration of visual features.

Together with previous findings on the integration of spatial and nonspatial visual features (e.g., Hommel, 1998, 2007; Hommel & Colzato, 2004), the present observations allow for a more specific theoretical conceptualization of visual feature integration. On the one hand, the present findings support Treisman's claim that integrating visual features is mediated by spatial location (Treisman, 1992, 1998; Treisman & Gormican, 1988). Hence, if two given features fall into the same spatial location, their values are integrated into a temporary binding. These linkages are presumably of a binary nature (Hommel, 2007; Hommel & Colzato, 2004), as indicated by the widespread absence of higher order interactions between feature repetition effects (i.e., effects involving more than two features or response). Taken together, the available observations suggest that location-based feature integration precedes and presumably constitutes the creation of object representations. On the other hand, however, the available evidence does not support the assumption of Kahneman et al. (1992) that location necessarily mediates object-file retrieval. Evidence from attentional studies (Hommel, 1998, 2007; Hommel & Colzato, 2004) and from developmental research (Leslie, Xu, Tremoulet, & Scholl, 1998) suggests that feature bindings do not necessarily need to include spatial codes to be retrieved, and even if spatial codes are involved, retrieval of nonspatial feature codes does not require the repetition of spatial location to occur. In other words, any feature match between the present and the preceding stimulus can induce object-file retrieval.

This implies that spatial location plays at least two different, dissociable roles or functions in the creation of object files: For one, it is used implicitly to define the feature codes that are likely to belong to the same object and that should be integrated into the same object file. Hence, the location of nonspatial feature designs decides into which object file a given feature will be integrated. This is the *selection function* emphasized by Treisman (1998) and others, and is commonly referred to as *attentional spotlight* or as locations on a *master map* of locations. For another, location is coded explicitly, and this code becomes an integral part of the object file at hand. This explicit code is used to retrieve stored object files whenever an object appears that shares and matches this code. This is the *indexing function* addressed by Kahneman et al. (1992). However, in contrast to the original idea of Kahneman et al., object files may also be indexed by other than spatial codes; in fact, any feature match seems to induce the retrieval of feature-overlapping object files.

The claim that spatial location plays a crucial role in the selection for feature integration is not only suggested by the present observations but also is consistent with findings from studies of visual short-term memory. Such studies have rather consistently shown that reporting two visual features is easier if they belong to the same object (e.g., Duncan, 1984, 1993). However, Xu (2006) has pointed out that most relevant studies confounded objecthood with proximity: Features belonging to the same object also happened to fall into the same location (see Baylis & Driver, 1993, for an exception). In her own

study, Xu found strong evidence that spatial proximity plays a major role in producing benefits of "objecthood." With the present observations, this suggests that at least some "object benefits" may actually represent feature-conjunction benefits resulting from sharing the same location and, thus, becoming part of the same object file. One may rightly argue that tasks involving short-term or working memory do not provide process-pure measures of feature integration, given that they do not only require feature encoding but also consolidation, maintenance, and retrieval processes, which may be affected by or make use of location information. This criticism does not apply to the preview design employed in the present study, however. There is no need to encode, consolidate, maintain, or retrieve any of the features of S1, nor is there any need to integrate the features in the first place. Accordingly, this task might be considered to provide the most conservative and process-pure measure of feature integration available. If so, the indication that spatial proximity still plays a crucial role in the selection for binding is particularly telling.

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