Connectedness and the Integration of Parts With Relations in Shape Perception

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Seven experiments investigated whether part connectedness would facilitate the perception of spatial relations among object parts. Experiments 1–4 showed that objects composed of connected parts are easier to distinguish from distractors in rapid serial visual presentation sequences than objects composed of separated parts and that this effect cannot be attributed to the presence of local features in the connected images. Experiments 5 and 6 revealed that image-based connectedness is neither necessary nor sufficient for the connectedness effect, and Experiment 7 showed that the connectedness effect is not a simple feature conjunction effect (i.e., it does not hold in a shape–color conjunction search task). These findings are consistent with the claim, central to the structural description theories, that the visual system not only decomposes objects into parts but also explicitly integrates those parts with their spatial relations.

Shape plays a central role in human object recognition. Numerous researchers have proposed that the human visual system represents an object’s shape as a structural description specifying the object’s features or parts in terms of their relations to one another (Biederman, 1987; Hummel & Biederman, 1992; Marr, 1982; Marr & Nishihara, 1978; Rock, 1983). For example, a human body might be represented as a hierarchical collection of cylinders end-connected in specific ways (Marr & Nishihara, 1978), and a briefcase might be represented as a curved cylinder (the handle) end-attached to the top of a slab (the body; Biederman, 1987). In this view, object recognition proceeds in two general stages. In the first, the visual system segments an object’s image into its parts and computes the spatial relations between them; in the second, the parts and relations are matched to memory for recognition (see, e.g., Hummel & Biederman, 1992; Marr & Nishihara, 1978).

If this account is correct, then the visual system is faced with a difficult computational problem: Spatial relations are expensive to compute and represent. It is infeasible to predesignate separate representational units (e.g., “symbols” or neurons) for all possible parts in all possible relations. Rather, a structural description must be generated on the fly by actively binding parts into relational structures (i.e., binding the representation of each part to a representation of its relations to other parts; Hummel & Biederman, 1992). Importantly, this process takes time and consumes processing resources (e.g., attention; see Hummel & Stankiewicz, 1996). Moreover, the number of relations to be represented (and the time and resources required to represent them) grows with the square of the number of parts in the object. If structural descriptions play a role in object perception, then a fundamental problem is to compute and represent these relations efficiently.

A related problem derives from the fact that visual images usually contain multiple objects. In an image containing two 5-part objects (a total of 10 parts), only 10 of the 45 part-to-part relations will belong to any single object (for a total of 20 within-objects relations); the remaining 25 refer to parts of different objects. Such between-objects relations are irrelevant to the identity of either object and, included as part of an object's visual representation, would interfere with recognition. For example, the fact that the handle of one's coffee mug is to the left of one's computer screen is irrelevant to the identity of either the mug or computer. The problem of determining which relations belong together as properties of a single object is related to the familiar figure–ground segmentation problem, but here the problem is to determine which relations belong together rather than to determine which features belong together. The rapid growth in the number of relations with the number of parts in an image, and the problem of ignoring between-objects relations, suggests that the visual system must somehow decide which relations to compute before attempting object recognition. How might the visual system make an intelligent guess about which relations to compute and which to ignore?

There are at least two potential solutions to this problem. One is to represent shape in terms of a few large parts, such as geons (Biederman, 1987), rather than many small features, such as lines and vertices. Part-based representations have other advantages as well (see Biederman, 1987; Binford, 1971; Dickinson, Pentland, & Rosenfeld, 1992; Marr, 1982), and there is empirical evidence for the role of parts in human object recognition (Biederman, 1987; Bieder-
man & Cooper, 1991). Representing objects in terms of large parts rather than small features reduces the number of relations it is necessary to compute, but it does not address the problem of distinguishing within- from between-objects relations. This problem requires a different solution.

This problem is difficult because it is less constrained than the problem of grouping local image features into geons. Geons are finite in number and bear well-defined relationships to local image features (e.g., contours tend to terminate when they belong to the same geon, but not when they belong to separate geons), making it possible to define bottom-up constraints for grouping image features into geons (Biederman, 1987; Hummel & Biederman, 1992; see also Dickinson et al., 1992; Donnelly, Humphreys, & Riddoch, 1991; Elder & Zucker, 1993; Hoffman & Richards, 1984; Lowe, 1987). However, object representations are not recursively hierarchical. Although the part–whole relations between features and geons can be understood in terms of geometric principles, part–whole relations between geons and objects cannot: Geons can combine into objects in virtually any configuration (Biederman, 1987). What is needed, therefore, is a heuristic for making an initial bottom-up guess about whether a given pair of geons likely belongs to the same object. Given evidence that two geons belong to the same object, it may be worthwhile to compute the spatial relations between them, but given evidence that they belong to different objects, it is probably better to ignore their relations for the purposes of object recognition.

The main purpose of this research was to investigate one heuristic the visual system may use to distinguish within-from between-objects relations before recognition: the heuristic of connectedness. A related purpose was to investigate whether the visual system represents or processes within-objects relations differently than it represents and processes between-objects relations. In the following sections, we describe the connectedness hypothesis and relate it to previous work on object perception.

CONNECTEDNESS AS A CONSTRAINT ON THE DETECTION OF WITHIN-OBJECTS SPATIAL RELATIONS

It is important to distinguish connectedness in the two-dimensional (2-D) image (image connectedness) from connectedness in the 3-D world (physical connectedness). We refer to two parts as physically connected when one physically touches the other (in the 3-D world). Under normal circumstances, every part of an object will be physically connected to at least one other part. Of course, it is rare that every part of an object will be directly connected to every other (e.g., in the case of the human body, the head and torso are not directly connected), but parts that are not directly connected will be indirectly connected, in that they will lie on a chain of parts that are directly connected (e.g., the head is directly connected to the neck and the neck is directly connected to the torso). Physical connectedness (direct or indirect) is thus a necessary condition for two parts to belong to the same object. Even though it does not guarantee that two parts belong to the same object (e.g., a cup is physically connected to the table on which it sits even though the two are separate objects), a lack of physical connectedness (direct or indirect) virtually guarantees that the parts do not belong to the same object. Perceptual cues suggesting the presence or absence of physical connectedness may therefore provide a useful basis for distinguishing within-from between-objects relations before object recognition.

Image connectedness is one such cue. Image connectedness is a property of the 2-D projection of two 3-D parts in which the bounding contours of one part either touch or completely contain the bounding contours of the other. When two parts are physically connected in 3-D, their projections will tend to be image connected in any image in which both are visible (unless the join is occluded, as elaborated on shortly). This regularity suggests an important heuristic for selecting relations before recognition: Ignore the spatial relations between parts that are not image connected. This simple heuristic would substantially reduce the number of relations computed among the parts in any given image. Importantly, the proportion of between-objects relations ignored on this basis will tend to be greater than the proportion of within-objects relations ignored. The first four experiments reported here tested the hypothesis that the visual system uses image connectedness as a cue for selecting relations between parts in a visual image. In brief, the results suggest that it does.

Although image connectedness is a potentially useful cue, it is neither necessary nor sufficient for inferring physical connectedness. It is not necessary because two parts can be physically connected without being image connected, as when the join is occluded by another part or surface. Likewise, if one part is partly occluded so that it projects as two separate regions in the image, then one region will not be directly image connected, either to the other region of the same part or to the other part. In such cases, other perceptual cues, such as collinearity or cocircularity, may serve as cues for perceptually relating the regions (see, e.g., Kellman & Shipley, 1991) and computing the parts' relations. In Experiment 5 we investigated whether image connectedness is necessary for inferring physical connectedness and found that it is not. Image connectedness also is not sufficient for inferring physical connectedness. Anytime one part occludes another, their projections will be image connected even if the parts themselves are not physically connected. In Experiment 6 we investigated whether image connectedness is sufficient for the selection of part-to-part relations and found that it is not.

Palmer and Rock (1994) proposed connectedness as a cue for perceptual organization and reported various findings consistent with this proposal. They distinguished between two kinds of connectedness: uniform and element. Uniform connectedness results in unit formation, in which the connected elements lose their status as independent perceptual entities (analogous to the grouping of local image features into parts). Element connectedness results in perceptual grouping, but the connected elements remain independent perceptual entities (in much the same way that parts can be grouped into objects but still remain perceptually distinct). Our use of "connectedness" corresponds to element
In the experiments reported here, we operationally defined within-objects relations as relations between image-connected parts (i.e., relations between parts that would be grouped by Palmer & Rock's element connectedness) and between-objects relations as relations between parts that are not image connected (i.e., do not satisfy element connectedness).

COMPARISON OF WITHIN- AND BETWEEN-OBJECTS RELATIONS

Several researchers have investigated issues related to the issue of within- versus between-objects relations (Baylis, 1994; Baylis & Driver, 1993; Elder & Zucker, 1993; Enns, 1992; Humphreys & Riddoch, 1993; Saiki & Hummel, in press, also see Humphreys & Riddoch, 1994, 1995, for neuropsychological evidence), but the majority of this work has dealt with the relations among simple features rather than the relations among convex parts (i.e., relations that would result in Palmer & Rock's, 1994, uniform connectedness). For example, using a visual search paradigm, Donnelly et al. (1991) showed that an L vertex will pop out from a field of otherwise similar vertices if the distractor vertices (but not the target) form the corners of a polygon. This finding suggests that participants preattentively grouped the distractor vertices, segmenting them from the target. Similarly, Enns (1992) showed that a cubelike figure at one orientation in depth will pop out from an array of cubes at a different orientation in depth, suggesting that the relations among local image features (i.e., whether the contours group to form a cube facing one way or another) is computed preattentively. Similarly, Baylis and Driver (1993) showed that it is easier to judge the relative height of two vertices when they belong to the same figure than when they belong to different figures, and Elder and Zucker (1993) showed that closed 2-D figures are easier to detect in a visual search task than are open figures. These findings suggest that people process features differently depending on whether they group into objectlike sets, and they are typically interpreted in the context of the within- versus between-objects distinction. However, these experiments used simple, convex forms as stimuli. Donnelly et al. (1991) used polygons, Enns (1992) used cubes, Baylis and Driver (1993) used hexagons and pentagons, and Elder and Zucker (1993) used hexagons. All these stimuli correspond to our definition of parts, not multipart objects (see also Biederman, 1987; Hoffman & Richards, 1984). In our terminology, these findings speak to the distinction between within- versus between-objects relations rather than the distinction between within- versus between-parts relations.

A study by Logan (1994) is more directly relevant to the issue of within- versus between-objects relations. Logan had participants search for targets defined by two simple figures in a specific spatial relation (e.g., a dash [-] above a plus [+]). He compared their ability to detect targets in which the dash and plus were connected with their ability to detect targets in which the dash and plus were separated and found no significant differences between these conditions. However, there are a few difficulties with this study as a comparison of within- and between-objects relations. First, the task required participants to map linguistic representations onto perceptual representations. Rather than viewing examples of the targets before searching for them, participants were verbally instructed to search for a particular type of target (e.g., "look for a dash above a plus"). The lack of effect for within- versus between-objects relations may reflect the way in which participants mapped verbal representations onto visual ones. If participants tended to map "dash above plus" onto a between-objects (separated) representation, then this may have offset any advantage in the perception of connected relations over separated relations. Second, although it was not statistically reliable, Logan's data showed a trend toward better performance in the connected condition than in the separated condition. Third, it is, of course, impossible to conclude anything with certainty on the basis of a null result. It is possible that Logan's paradigm was simply not sensitive enough to detect any differences between within- and between-objects relations, especially if those differences are small.

In summary, there is evidence for a perceptual advantage in the processing of features that can be grouped into a single part (within-parts advantage), but there are no data showing an analogous within-objects advantage in the processing of the spatial relations between the separate parts of an object. The question of whether there might be such an advantage—and whether that advantage is sensitive to perceptual cues suggesting physical connectedness—is the primary focus of the research reported here.

TEMPORAL VISUAL SEARCH AS AN EXPERIMENTAL PARADIGM

We used a rapid serial visual presentation (RSVP) paradigm to investigate participants' sensitivity to the relations between connected and separated parts. Participants viewed RSVP sequences of eight simple, two-part objects. Their task was to determine whether a sequence contained a target object, shown beforehand. Each sequence contained two critical items: either one target and one distractor (target-present trials) or two distractors (target-absent trials). The remaining six items were fillers. Distractors were designed to produce detection errors (i.e., false alarms and misses) in response to various types of part–relation integration (as elaborated on later). To respond correctly on a given trial, a participant had to correctly integrate (bind) the parts and relations into a representation of a single object. The primary manipulation was whether the parts of the critical items were connected (the connected condition) or not (the separated condition). If connectedness plays a role in people's ability to integrate an object's parts with their relations, then target detection should be better in the connected condition than in the separated condition.

This kind of temporal visual search task (i.e., target detection in an RSVP sequence) affords several advantages over conventional spatial search task as a paradigm for investigating the effects of perceptual grouping on spatial relations in shape perception. Perceptual grouping is sensitive to various spatial factors such as the proximity and
configuration of the elements in a display, so spatial search displays introduce additional grouping cues that may influence participants' responses to target items (Duncan & Humphreys, 1989; Humphreys, Quinlan, & Riddoch, 1989). Second, in a spatial search task (Prinzmetal, 1981), it is not clear whether correct rejections (i.e., "absent" responses on target-absent trials) indicate that participants correctly conjoined the features of the distractors, or simply failed to conjoin them (thereby "failing" to see the [absent] target). By contrast, as detailed later, the temporal search task used here required participants to integrate an object's parts with their spatial relations on both target-present and -absent trials. Third, RSVP sequences are known to produce visual binding (integration) errors (Intraub, 1985, 1989).

In the first four experiments we tested the hypothesis that image connectedness plays a role in people's ability to integrate an object's parts and relations into a single percept. Experiment 1 demonstrated that connectedness facilitates part–relation integration, and Experiments 2–4 tested alternative explanations of this effect. Experiment 5 examined whether image connectedness is necessary for the observed effect, and Experiment 6 examined whether it is sufficient. Experiment 7 examined whether the effects observed in Experiments 1–6 specifically reflect the properties of part–relation integration or simply a peculiarity of the temporal search task.

**GENERAL METHOD**

**Design**

There were three within-subjects variables: connectedness (connected vs. separated), number of fillers intervening between the two critical items in a sequence (0 vs. 1), and conjunction type (Part 1–relation, Part 2–relation, and Part 1–Part 2, as elaborated on later). The primary dependent variable was the percentage correct.\(^1\)

We used this measure because, in our paradigm, (in contrast to a spatial visual search task), connectedness effects may appear either as false alarms or as misses. False-alarm and miss rates were used as secondary dependent variables.

**Materials**

**Stimuli**

Stimuli were filled line drawings of 2-D objects composed of two distinct parts. One part was red and the other was blue (except in Experiment 5). RSVP sequences contained both critical items and fillers. Targets and distractors were chosen from a set of critical items. Critical items were defined by three attributes: the shape of Part 1 (Part 1), the shape of Part 2 (Part 2), and the position of Part 1 relative to Part 2 (relation). In connected critical items, Parts 1 and 2 were image connected (i.e., their contours met at least one point in the image); in separated critical items, Parts 1 and 2 were placed 2.5–4 mm apart (depending on the experiment), so that their contours did not meet at any point in the image. Critical items differed across experiments. Detailed descriptions are given in the context of the individual experiments.

Each experimental trial (i.e., each RSVP sequence) contained two critical items. In target-absent sequences, both critical items were distractors (primary distractors). In target-present sequences, one critical item was a target and one was a secondary distractor.

Our primary interest in these experiments was participants' ability to integrate (bind) the objects' parts and relations into a single percept. Therefore, targets and distractors were defined by conjunctions of parts and relations, and primary distractors were designed to produce "illusory targets" in the event of binding errors (e.g., where a part in one distractor is incorrectly bound to a relation in the other). There were three conjunction type conditions: Part 1–relation, Part 2–relation, and Part 1–Part 2. The name of a condition indicates which binding (property conjunction) was critical for target–distractor discrimination in that condition. For example, in the Part 1–relation condition, one primary distractor shared the shape of Part 1 with the target and one shared the relation between the parts; a perceptual misbinding of Part 1 from one primary distractor with the spatial relation from the other would produce an "illusory target" (see Figure 1). In the Part 2–relation condition, the critical conjunction is the Part 2–relation conjunction, so a misbinding of Part 2 from one distractor with the spatial relation from the other would produce an illusory target. In the Part 1–Part 2 condition, a misbinding of Part 1 from one distractor with Part 2 from the other would produce an illusory target. Target-present trials in all conditions contained both a target and a secondary distractor. In each condition, the secondary distractor was formed from the constant property in that condition and from the properties different from those of the target in the other two attributes. For example, in the Part 1–relation condition, Part 2 was constant across all stimuli, and the values of relation and Part 1 in the secondary distractor differed from those of the target (see Figure 1). Table 1 is a summary of how the conjunction type conditions were defined in each experiment.

There were eight filler items, as shown in Figure 2, all different from the critical items. Half were connected and half separated. All objects were approximately 3.5 X 3.5 cm and subtended a visual angle of 1.3° (participants sat 150 cm from the display).

**RSVP Sequences**

Every RSVP sequence contained eight items. On practice trials, each sequence contained one critical item and seven fillers; experimental sequences contained two critical items and six fillers. Fillers were randomly selected from the eight filler objects, so even when the critical items were connected, some fillers were separated and vice versa. The first and the last items in any sequence were always fillers. The serial positions of filler items were randomly determined for each trial. Each practice sequence contained either one target or one primary distractor that appeared equally often in each of the six serial positions from 2 to 7. Experimental trials always contained two critical items, a target, and a secondary distractor (target-present trials) or two primary distractors (target-absent trials). Critical items appeared equally often in each of the six serial positions from 2 to 7. The presentation order of critical items was counterbalanced across trials. There were 24 types of sequences obtained by orthogonally crossing: (a) target present versus target absent, (b) conjunction type (Part 1–relation, Part 2–relation, or Part 1–Part 2), (c) connected versus separated, and (d) number of intervening fillers (0 or 1). Experimental trials were grouped into blocks of 12. Connectedness varied only between

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\(^1\) We also calculated a score in which the percentage correct was weighted by participants' confidence ratings, but this measure showed essentially the same pattern of results as the percentage correct. Thus, we report only the percentage of correct data in this article.
blocks (i.e., within a block, critical items were either all connected or all separated). All other variables (i.e., conjunction type, number of intervening fillers, and target present vs. absent) varied within blocks.

Procedure

Participants were run individually on a Macintosh IIci with an Apple color monitor. A program written in MacProbe (Hunt, 1993) controlled the whole experimental session. Participants were first given written instructions stating that their task was to detect a target picture in a rapid sequence of pictures. To familiarize them with the objects, participants were shown all the filler and critical items. They were permitted to view them as long as they wished. Next, there were two blocks of 18 practice trials: 9 target-present and 9 target-absent trials. The same critical item served as a target throughout an entire block. One practice block used connected critical items (connected block), and the other used separated critical items (separated block). The order of connected and separated blocks was counterbalanced across participants.

Table 1

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Main characteristic</th>
<th>Part 1</th>
<th>Part 2</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Part 1 and Part 2 are equal size</td>
<td>Trapezoid</td>
<td>Vertical</td>
<td>Part 1 above Part 2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Eye shape</td>
<td>Horizontal</td>
<td>Part 1 right of Part 2</td>
</tr>
<tr>
<td>Small 1</td>
<td>Part 1 is smaller than Part 2</td>
<td>Trapezoid</td>
<td>Vertical</td>
<td>Part 1 above Part 2</td>
</tr>
<tr>
<td>Small 2</td>
<td>Part 2 is smaller than Part 1</td>
<td>Eye shape</td>
<td>Horizontal</td>
<td>Part 1 right of Part 2</td>
</tr>
<tr>
<td>3</td>
<td>Smaller Part 2 and no support relation</td>
<td>Trapezoid</td>
<td>Vertical</td>
<td>Part 1 below Part 2</td>
</tr>
<tr>
<td>4</td>
<td>Cusp shape controlled</td>
<td>Eye shape</td>
<td>Horizontal</td>
<td>Part 1 left of Part 2</td>
</tr>
<tr>
<td>5</td>
<td>Collinearity</td>
<td>Polygon</td>
<td>Vertical</td>
<td>Part 1 above Part 2</td>
</tr>
<tr>
<td>6</td>
<td>Coplanarity (3-D shape)</td>
<td>Curved</td>
<td>Horizontal</td>
<td>Part 1 right of Part 2</td>
</tr>
<tr>
<td>7</td>
<td>Color change right–left only</td>
<td>Shape A</td>
<td>Shape C</td>
<td>Part 1 above Part 2</td>
</tr>
</tbody>
</table>

Note. The part shapes in Experiment 5 were difficult to name, so the symbols A, B, C, and D are used for the sake of illustration.
Figure 2. Filler items used in Experiments 1-7.

separated practice blocks was counterbalanced between participants. During the practice blocks, target-absent trials were divided into three types: relation trials, in which the distractor differed from the target in the relation between Parts 1 and 2; Part 1 trials, in which the distractor differed from the target in the shape of Part 1; and Part 2 trials, in which the distractor differed from the target in the shape of Part 2. There were three trials of each type ordered randomly. When a participant responded incorrectly on a given practice trial, that trial was moved to the end of the block and given again, so that the exact number of practice trials varied from participant to participant.

There were 26 experimental blocks, each with 12 trials. The first 2 served as warm-up and were not included in analyses. Throughout each block, a single critical item served as a target. Half the blocks were connected and half were separated. Blocks were grouped into connected and separated pairs and ordered so that connected and separated blocks did not appear in regular alternation. The order of the connected and separated blocks was counterbalanced such that half the participants received one order and half received the reverse order. For each participant, four of the eight connected critical items served as connected targets, and the corresponding separated critical items served as separated targets. Corresponding connected and separated critical items were never used as targets in consecutive blocks. Blocks were thus organized into sets of eight, in which each set used four connected targets and the corresponding four separated targets. Each set was presented three times (for a total of 24 blocks). Although sets were identical in terms of the critical items they used, they differed in the serial positions of the critical items with the RSVP sequences and in the ordering of trials within blocks. The selection of target objects was counterbalanced across participants using a Latin square design so that each critical item served as a target equally often.

Each block contained 12 trials, orthogonally varying conjunction type, number of intervening fillers, and target present or absent. These trials were ordered randomly within blocks, so it was impossible to predict which type of conjunction (or number of fillers) would be instrumental on a given trial. The serial positions of critical items were counterbalanced for each participant so that critical items appeared equally often at each serial position from 2 to 7 across blocks. The target for a given block was displayed at the beginning of the block and after every 6 trials (Experiments 1, 2, 3, and 7) or every 4 trials (Experiments 4, 5, and 6) within the block. The target was displayed in the upper center of the screen outside the area in which sequences were presented. Participants were permitted to look at the target as long as they wished and resumed the trials with a keypress. A participant's cumulative percentage of correct responses was displayed after every two blocks. Participants were instructed to rest when the target or percentage correct was displayed and not to rest at other times.

Figure 3 illustrates an RSVP sequence. Each trial began with a fixation cross (+) at the center of the screen for 500 ms, followed by a sequence of eight pictures. Exposure duration was set using a staircase procedure, as described later. The exact location of each picture on the screen varied within and between sequences. Each picture was centered at a location randomly chosen from a 1.9 × 1.9 cm square in the center of the screen (the diagonal of this square subtended approximately 1.0°). After the sequence, the participants indicated whether the target was present by pressing a key. They were instructed to be as accurate as possible but were not instructed to respond rapidly. Participants rated their confidence in each judgment as “guess,” “maybe,” or “confident.” They received accuracy feedback after the confidence rating. Incorrect responses were followed by a beep. The next trial began approximately 1 s after the feedback.

To equate the exposure duration for connected and separated targets, exposure duration was varied using the following staircase procedure. On the first two experimental blocks, each picture in a sequence was displayed for 180 ms. The participant's percentage correct was calculated for each pair of blocks. (Recall that each pair contained one connected and one separated block.) If more than 90% of the responses were correct on pair \( N \), then the exposure duration was reduced by 15 ms on pair \( N + 1 \). If 60–75% of their responses were correct, then the exposure duration increased by 15 ms on pair \( N + 1 \). If fewer than 60% of their responses were correct, then the exposure duration was increased by 30 ms on pair \( N + 1 \). This procedure was designed to keep participants' accuracy between 75% and 85%.
CONNECTEDNESS AND SHAPE PERCEPTION

EFFECTS OF CONNECTEDNESS IN TEMPORAL VISUAL SEARCH

In the first four experiments we explored the difference between within- and between-objects relations by testing the effects of image connectedness on participants’ performance in a temporal visual search task.

Experiment 1: Initial Demonstration

The main purpose of Experiment 1 was to test whether image connectedness would affect participants’ ability to integrate the shapes and spatial relations of an object’s parts. Objects were composed of asymmetrical parts with clear main axes,2 because a pilot experiment using large symmetrical parts showed reduced effects of connectedness.

Method

Participants

Twenty-four undergraduates at the University of California, Los Angeles (UCLA), participated for credit in introductory psychology courses. All had normal or corrected-to-normal vision.

Materials

Figure 4 shows the critical items used in this experiment. The object parts were asymmetrical and had clear main axes. Part 1 was either a trapezoid or an eyelike shape. Part 2 was one of two irregular shapes as shown in Figure 4. We refer to the Part 2 with the vertical main axis as “vertical” and the Part 2 with the horizontal main axis as “horizontal.” In the connected stimuli, the eyelike shape was 1.3 cm (0.5°) × 2.7 cm (1.0°), the trapezoid was 2.5 cm (0.9°) × 1.7 cm (0.7°), the horizontal Part 2 was 2.5 cm (0.9°) × 1.8 cm (0.7°), and the vertical was 1.5 cm (0.6°) × 2.5 cm (0.9°). The complete objects were 0.7°–1.9° high and 1.0°–2.0° wide. Separated critical items were made by scaling Parts 1 and 2 to 90% of their original size, then moving them to make the horizontal lengths of the stimuli with the beside relation and the vertical lengths of stimuli with the above relation the same as those of corresponding connected objects. The gap between the parts of the separated objects subtended approximately 0.2° of visual angle.

Procedure

The experiment was run as described in the General Method section.

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2 Some parts are arguably divisible into subparts because of the concavity in the bounding contour. However, even if participants perceptually divide our parts into pairs of subparts, part complexity is still equivalent across the connected and separated stimuli. On the basis of pilot data, we designed the parts to meet three criteria: (a) They had to be asymmetric, (b) they had to be individually easily discriminable, and (c) complete objects formed from the parts could not resemble any familiar object. Using simple parts (e.g., rectangles) would violate the first criterion.
the experimental trials in this experiment was 208 ms; the minimum and maximum were 165 and 289 ms, respectively.

**Percentage Correct**

The percentage of correct responses as a function of condition is shown in Figure 5. A 2 (connectedness) × 2 (number of fillers) × 3 (conjunction type) multivariate analysis of variance (MANOVA) revealed significant main effects of connectedness, $F(1, 23) = 19.89, p < .0001$, $MSE = 43.63$, number of fillers, $F(1, 23) = 53.13, p < .0001$, $MSE = 64.27$, and conjunction type, Wilk's $\lambda = .243$, exact $F(2, 22) = 34.25, p < .0001$. The interaction between number of fillers and connectedness was marginally significant, $F(1, 23) = 3.06, p = .094$, $MSE = 57.40$. None of the other interactions were statistically significant. Overall, the results reveal (a) more correct responses on connected trials than on separated trials, (b) more correct responses on 1 filler trials than on 0 filler trials, and (c) the greatest percentage of correct responses with the Part 1-relation conjunction type and the lowest with the Part 1–Part 2 conjunction type.

We also conducted separate 2 (connectedness) × 2 (number of fillers) analyses of variance (ANOVAs) for each conjunction type. All three conditions showed a significant main effect of connectedness, $F(1, 23) = 8.27, p < .01$, $MSE = 26.79$, for Part 1-relation, $F(1, 23) = 10.30, p < .005$, $MSE = 26.72$, for Part 2-relation, and $F(1, 23) = 5.73, p < .025$, $MSE = 66.75$, for Part 1–Part 2.

**False Alarms and Misses**

False alarms and misses also were calculated for each participant. Mean false-alarm and miss rates for connected and separated conditions in Experiments 1–7 are shown in Table 3. In general, there were more false alarms than misses. Importantly, the effect of connectedness was observed with both measures. The mean false-alarm rate in the connected condition was significantly lower than the mean false-alarm rate in the separated condition, $F(1, 23) = 9.27, p < .01$, $MSE = 17.75$. Similarly, the mean miss rate in the connected condition was significantly lower than the mean miss rate in the separated condition, $F(1, 23) = 11.00, p < .005$, $MSE = 11.46$. The effects of other experimental variables (e.g., conjunction type and number of fillers) with these measures was basically the same as with percentage correct. In subsequent experiments, analyses of false alarms and misses are reported only when the pattern of results differed from the general pattern found in Experiment 1.

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**Results**

**Exposure Duration**

Because exposure duration was set on the basis of a participant's error rate, the mean exposure duration in an experiment roughly reflected the difficulty of the task in that experiment. The mean exposure durations in all experiments are summarized in Table 2. The mean exposure duration on

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Exposure duration</th>
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<tbody>
<tr>
<td>1</td>
<td>208</td>
</tr>
<tr>
<td>2</td>
<td>171</td>
</tr>
<tr>
<td>Small 1</td>
<td>189</td>
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<tr>
<td>Small 2</td>
<td>184</td>
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<tr>
<td>3</td>
<td>206</td>
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<td>4</td>
<td>239</td>
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<td>6</td>
<td>201</td>
</tr>
<tr>
<td>7</td>
<td>201</td>
</tr>
</tbody>
</table>

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3 We analyzed the data using multivariate analyses of variance. We tested main effects and interactions involving variables with more than two levels using a multivariate test whenever the sphericity assumption of the covariance matrix was not violated. We used Mauchly's test of sphericity and report the value of Wilk's lambda and the exact $F$ statistic derived from it. When sphericity was violated, we reported the results of Greenhouse–Geisser univariate tests with adjusted degrees of freedom.
Discussion

Target detection was more accurate on connected trials than on separated trials, suggesting that (at least in our task) it is easier to detect a target defined by a pair of parts in a specific spatial relation when the parts are image connected than when they are separated. The strong main effect of the number of fillers suggests that the observed errors—both false alarms and misses—are not solely failures of feature detection. If participants were simply unable to detect the appropriate target parts or relations (e.g., because of the rapid displays), then there would be no reason to expect the number of fillers intervening between the critical objects to affect target detection. In turn, this observation suggests that at least some of the errors, especially in the 0 filler condition, are binding errors: Apparently, participants were better able to integrate (bind) an object's parts with their relations when they were image connected, and therefore formed a perceptual group, than when they were not.

The results of Experiment 1 also reveal two effects of conjunction type. There were more errors in the Part 1–Part 2 condition than in either other condition, and there were more errors in the Part 2–relation condition than in the Part 1–relation condition. The difficulty of Part 1–Part 2 conjunctions (relative to Part 1–relation and Part 2–relation conjunctions) likely reflects one (or both) of two variables. First, it may be more difficult to integrate two part shapes into a whole object than to integrate the shape of one part with its relation to another. It also is possible that Part 1–Part 2 conjunctions are more difficult to detect simply because targets and distractors in this condition had more similar overall shapes (e.g., as defined by low spatial frequency image components or by the general locations of colored regions; see Figure 1). The difference in performance between the Part 1–relation and Part 2–relation conditions indicates that participants had greater difficulty integrating the shape of Part 1 with its relation (to Part 2) than the shape of Part 2 with its relation (to Part 1). This effect suggests that spatial relations are asymmetrical: The relation of Part 1 to Part 2 is not the same as (or the simple complement of) the relation of Part 2 to Part 1.

There are at least two potential causes for this asymmetry. First, it is possible that people represent small parts relative to larger ones more explicitly (or more strongly) than vice versa (e.g., as proposed by Marr & Nishihara, 1978). This suggestion is supported by the results of a pilot experiment in which Part 1 was smaller than Part 2. In this experiment, Part 1–relation conjunctions were detected much more
accurately than Part 2–relation conjunctions. Moreover, the
connectedness effect was more pronounced in the Part
1–relation condition than in the Part 2–relation condition. In
Experiment 2 we tested this size-based asymmetry hypoth-
esis directly.

Support relations (e.g., in which one part appears to
physically support another) are another potential source of
asymmetries in the representation of spatial relations. It is
possible that supported parts are represented relative to
supporting parts more than vice versa (e.g., one is more
inclined to say "the mug is on the table" than "the table is
under the mug"). In the stimuli with the above–below
relation in Experiment 1, Part 2 was always below Part 1,
giving the impression that Part 2 was supporting Part 1 and
encouraging participants to represent Part 1 relative to Part 2
more than vice versa. This support-based asymmetry hypoth-
esis was tested in Experiment 3.

Regardless of its precise origin, the Part 1–relation versus
Part 2–relation asymmetry observed in Experiment 1 is
important because it suggests that spatial relations are
represented asymmetrically and that the connectedness
effect depends on the explicitness (or strength) with which
relations are represented. (Conversely, the magnitude of the
connectedness effect can serve as an index of the explicit-
ness of the representation of spatial relations.)

Experiment 2: Effects of Relative Size

According to the size-based asymmetry hypothesis, the
difference between the Part 1–relation and Part 2–relation
conditions observed in Experiment 1 reflects an asymmetry
in the representation of spatial relations attributable to the
parts' relative sizes. In Experiment 2 we tested this hypoth-
thesis by examining the effect of relative size on the connect-
edness and conjunction type effects. Experiment 2 used the
same basic stimuli as Experiment 1, modified so that one
part of each object was decidedly larger than the other. In
one condition, Part 1 was smaller than Part 2 (Small 1); in
another condition (Small 2), Part 2 was smaller than Part 1.
Parts 1 and 2 were the same shapes across these conditions.

The asymmetric relations hypothesis makes the following
predictions. In the Small 1 condition, Part 2 will be treated as
a reference part, so performance should be better—and the
connectedness effect should be more pronounced—with Part
1–relation conjunctions than with Part 2–relation conjunc-
tions. In the Small 2 condition, Part 1 should serve as a
reference part, so performance should be better (and the
connectedness effect more pronounced), with Part 2–relation
conjunctions than with Part 1–relation conjunctions.

Method

Participants

Forty-eight undergraduates at the UCLA participated for credit
in introductory psychology courses. All had normal or corrected-to-
normal vision.

Design

There were two between-participants conditions: Small 1 and
Small 2. Participants were randomly assigned to conditions. Otherwise, the design was identical to that of Experiment 1.

Materials

Figure 6 shows examples of the stimuli used in this experiment.
There were two stimulus sets: Small 1 and Small 2. The shapes of
Parts 1 and 2 were the same as in Experiment 1, but their relative
sizes were different. Stimuli in the Small 1 set were created as
follows. Part 1 was red and Part 2 was blue. In connected stimuli,
the eyelike shape (Part 1) was 0.7 cm (0.25°) X 1.4 cm (0.5°), the
trapezoid (Part 1) was 1.4 cm (0.5°) X 0.9 cm (0.3°), the horizontal
Part 2 was 3.0 cm (1.1°) X 2.1 cm (0.8°), and the vertical Part 2 was
1.7 cm (0.7°) X 3.2 cm (1.2°). The complete objects were 0.7°–1.6°
high and 0.8°–1.7° wide. The separated stimuli were created as in
Experiment 1. The large part (here Part 2) was reduced to 90% of
its original size, and a gap was created by moving the parts to make
the widths of the stimuli with the beside relation and the heights of
stimuli with the above relation the same as those in the correspond-
ing connected stimuli. The gap between the parts in the separated
stimuli subtended approximately 0.1° of visual angle. In both the
connected and separated Small 1 stimuli, Part 1 was much smaller
than Part 2.

The Small 2 set (see Figure 6) was created as follows. Part 1 was
blue and Part 2 was red. In connected stimuli, the eyelike shape
(Part 1) was 1.8 cm (0.7°) X 3.5 cm (1.3°), the trapezoid (Part 1)
was 3.2 cm (1.2°) X 2.1 cm (0.8°), the horizontal Part 2 was 1.2 cm
(0.45°) X 0.9 cm (0.3°), and the vertical Part 2 was 3.2 cm (1.2°) X
2.1 cm (0.8°). The complete objects were 0.7°–1.6° high and
0.8°–1.7° wide. The separated stimuli were created in the same way
as the Small 1 separated set. The gap between the parts subtended
approximately 0.1° of visual angle. In both the connected and
separated Small 2 stimuli, Part 2 was much smaller than Part 1.

Procedure

The procedure was identical to that used in the previous
experiment.

Results

Exposure Duration

In the Small 1 condition, the mean exposure duration was
171 ms, and the minimum and maximum values were 118
and 236 ms, respectively. In the Small 2 condition, the
corresponding values were 189, 139, and 254 ms, respect-
ively. The difference between the exposure durations was
marginally significant, t(46) = 1.94, p = .058, suggesting
that the Small 2 condition was slightly more difficult than
the Small 1 condition. Both these mean exposure durations
were shorter than those of Experiment 1.

Percentage Correct

The mean percentage of correct responses in the experi-
mental conditions is shown in Figure 7. As predicted, the
pattern of effects in the Small 1 condition differed from that
in the Small 2 condition. However, the patterns differed from
those predicted, and the differences between the two condi-
A. Small 1 Condition

Connected stimuli

Separated stimuli

Colors

Blue

Red

B. Small 2 Condition

Figure 6. Critical items used in Experiment 2.

A 2 (stimulus set) x 2 (connectedness) x 2 (the number of fillers) x 3 (conjunction type) mixed-design MANOVA revealed significant main effects of connectedness, F(1, 46) = 29.94, p < .0001, MSE = 64.96, number of fillers, F(1, 46) = 221.44, p < .0001, MSE = 57.50, and conjunction type, F(1.78, 81.74) = 38.28, p < .0001, MSE = 84.18, with adjusted degrees of freedom. The main effect of stimulus set was marginally significant, F(1, 46) = 3.17, p = .082, MSE = 87.62, reflecting a trend toward a higher percentage of correct responses in the Small 1 condition than in the Small 2 condition. This trend, like the trend observed with exposure duration, suggests that the Small 2 condition might have been slightly more difficult than the Small 1 condition. The interaction between number of fillers and conjunction type was marginally significant, F(1, 46) = 3.17, p = .082, MSE = 87.62, reflecting a trend toward a higher percentage of correct responses in the Small 1 condition than in the Small 2 condition. This trend, like the trend observed with exposure duration, suggests that the Small 2 condition might have been slightly more difficult than the Small 1 condition. The interaction between number of fillers and conjunction type, Wilks's λ = .718, exact F(2, 45) = 8.84, p < .001, between stimulus set and conjunction type, F(1.78, 81.74) = 7.72, p < .001, MSE = 84.18, with adjusted degrees of freedom, between connectedness and number of fillers, F(1, 46) = 4.28, MSE = 46.28, p < .05, and the three-way interaction between stimulus set, conjunction type, and number of fillers, Wilks’s λ = .774, exact F(2, 45) = 6.57, p < .005, were all statistically significant. No other interactions were significant. The interactions involving the variable of stimulus set suggested that performance in the Small 1 condition differed from performance in the Small 2 condition. We therefore conducted separate analyses for each.

**Small 1 condition.** Overall, the basic pattern of results in the Small 1 condition was similar to that of the pilot experiment but different from that of Experiment 1. A 2 (connectedness) x 2 (number of fillers) x 3 (conjunction type) MANOVA revealed significant main effects of connectedness, F(1, 23) = 13.20, p < .001, MSE = 66.89, number of fillers, F(1, 23) = 138.70, p < .0001, MSE = 38.34, and conjunction type, Wilks's A = .275, exact F(2, 22) = 28.97, p < .0001, and a significant interaction between number of fillers and conjunction type, Wilks's λ = .480, exact F(2, 22) = 11.90, p < .005. No other interactions were significant. Separate 2 (connectedness) x 2 (number of fillers) ANOVAs for each conjunction type revealed a pattern similar to that of the pilot experiment. There was a highly significant main effect of connectedness in the Part 1-relation condition, F(1, 23) = 18.75, p < .0001, MSE = 39.51, but the main effect of connectedness was only marginally significant in the Part 1–Part 2 condition, F(1, 23) = 3.65, p = .069, MSE = 67.92, and was not significant in the Part 2–relation condition, F(1, 23) = 0.99, p > .1, MSE = 72.73. Unlike Experiment 1, which showed a significant connectedness effect in all three conjunction type
Figure 7. Mean percentage of correct responses by condition in Experiment 2.
conditions, the Small 1 condition revealed a significant connectedness effect only in the Part 1-relation condition.

**Small 2 condition.** Overall, the basic pattern of results was similar to that of Experiment 1 rather than a reverse of the pattern observed in the Small 1 condition. A 2 (connectedness) × 2 (number of fillers) × 3 (conjunction type) MANOVA revealed significant main effects of connectedness, $F(1, 23) = 16.92, p < .0001, MSE = 63.03$, number of fillers, $F(1, 23) = 97.96, p < .0001, MSE = 76.67$, and conjunction type, Wilk's $\lambda = .477, \text{exact } F(2, 22) = 12.05, p < .0001$, and a significant interaction between number of fillers and conjunction type, Wilk's $\lambda = .618, \text{exact } F(2, 22) = 6.80, p < .005$. None of the interactions involving connectedness were significant (a pattern similar to that of Experiment 1). Separate 2 (connectedness) × 2 (number of fillers) ANOVAs revealed significant main effects of connectedness with each conjunction type, $F(1, 23) = 6.73, p < .025, MSE = 54.44,$ for Part 1-relation, $F(1, 23) = 6.17, p < .025, MSE = 49.26,$ for Part 2-relation, and $F(1, 23) = 6.55, p < .025, MSE = 60.94$, for Part 1–Part 2.

**Discussion**

This experiment replicated the basic connectedness effect in both the Small 1 and Small 2 conditions, but, importantly, the specific pattern of effects differed between these conditions. The size-based asymmetry hypothesis was only partially supported. According to this hypothesis, relations are asymmetrical in that small parts are represented relative to larger parts more than vice versa. This account predicts that the connectedness effect will be greatest in the Part 1–relation condition of the Small 1 condition and in the Part 2–relation condition of the Small 2 condition. Consistent with this prediction, the effect of connectedness in the Small 1 condition was significant only for Part 1–relation conjunctions. However, the data from the Small 2 condition ran counter to the size-based asymmetry hypothesis. Here, the effect of connectedness was significant for both Part 1–relation and Part 2–relation conjunctions. The simplest interpretation of this effect (i.e., of the lack of Connectedness × Conjunction Type interaction in the Small 2 condition) is that relations are not asymmetrical. However, this explanation is inconsistent with the interaction observed in the Small 1 condition.

An alternative explanation of the effects in the Small 2 condition is based on the support-based asymmetry hypothesis. According to this hypothesis, supported parts are represented relative to supporting parts more than vice versa (i.e., a supporting part serves as a reference part). Together, the size-based and support-based asymmetry hypotheses may account for the effects in both the Small 1 and Small 2 conditions. In the Small 2 condition, Part 2 was smaller than Part 1, and Part 1 was supported by Part 2: Each part could serve as a reference by a different constraint (Part 1 by size and Part 2 by support). If both support and size constrain the choice of a reference part for computing relations, then we might see little or no asymmetry (i.e., little or no interaction between connectedness and conjunction type) in this condition. In the Small 1 condition, by contrast, Part 2 would serve as the reference part both in terms of size (it is larger than Part 1) and in terms of support (it supports Part 1). In this condition, we would expect to see a strong asymmetry between the Part 1–relation and Part 2–relation conditions (which we did). Although this size-plus-support hypothesis provides an intuitive account of the data in both the Small 1 and Small 2 conditions, it is less parsimonious than the simple no-asymmetry account of the findings in the Small 2 condition. Experiment 3 was designed to test the plausibility of the support-plus-size asymmetry hypothesis by testing the predictions of the support-based asymmetry hypothesis.

**Experiment 3: Effect of Support Relation**

In Experiment 2, Part 2 was always below Part 1 (in stimuli with the above–below relation), which may have given the impression that it was supporting Part 1. If so, then Part 2 may have been treated as a reference part even when it was smaller than Part 1. In Experiment 3 we tested this possibility. We created the stimuli for this experiment by rotating the stimuli in the Small 2 condition 180° in the picture plane (see Figure 8), placing Part 1 either below or to the left of Part 2, so that Part 2 no longer appeared to support it. If the appearance of support was responsible for the
results in the Small 2 condition of Experiment 2 (as elaborated on earlier), then the results of this experiment would resemble a reversal of the Small 1 condition of Experiment 2 rather than a replication of the Small 2 condition of Experiment 2. Specifically, performance should be better and the connectedness effect should be more pronounced in the Part 2–relation condition than in the Part 1–relation condition of this experiment.

**Results**

### Exposure Duration

The mean exposure duration on the experimental trials was 184 ms; the minimum and maximum were 136 and 226 ms, respectively. These values were comparable to those of Experiment 2.

### Percentage Correct

The mean percentage of correct responses is shown in Figure 9. A 2 (connectedness) × 2 (number of fillers) × 3 (conjunction type) MANOVA revealed significant main effects of connectedness, $F(1, 23) = 38.00, p < .0001$, $MS_E = 28.91$, number of fillers, $F(1, 23) = 79.55, p < .0001$, $MS_E = 54.84$, and conjunction type, Wilks's $\lambda = .295$, exact $F(2, 22) = 26.30, p < .0001$. The interaction between number of fillers and conjunction type was significant, Wilks's $\lambda = .588$, exact $F(2, 22) = 7.70, p < .005$. None of the other interactions was statistically significant.

Separate 2 (connectedness) × 2 (number of fillers) ANOVAs revealed significant main effects of connectedness in the Part 2–relation condition, $F(1, 23) = 8.95, p < .01$, $MS_E = 37.36$, and in the Part 1–Part 2 condition, $F(1, 23) = 18.96, p < .0001$, $MS_E = 49.43$, but not in the Part 1–relation condition, $F(1, 23) = 1.28, p > .1$, $MS_E = 56.49$.

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**Method**

### Participants

Twenty-four undergraduates at the UCLA participated for credit in introductory psychology courses. All had normal or corrected-to-normal vision.

### Materials

Figure 8 shows the critical items used in this experiment. Each stimulus was formed by rotating one stimulus in the Small 2 condition of Experiment 2 by 180° in the picture plane. Part 1 was larger than and either below or to the left of Part 2. The stimuli were otherwise identical to those used in the Small 2 condition of Experiment 2.

### Procedure

The procedure was identical to that of the Small 2 condition of Experiment 2.
Discussion

The results of Experiment 3 are consistent with the suggestion that the apparent "supporting" relation caused participants to treat Part 2 as a reference part in the Small 2 condition of Experiment 2: In this experiment, which did not afford this interpretation, performance was better in the Part 2-relation condition than in the Part 1-relation condition, and the effect of connectedness was larger in the Part 2-relation condition than in the Part 1-relation condition. Combined with the results of Experiment 2, these results support the size-based and support-based asymmetry hypothesis. When two parts differ in size, the larger is likely to be treated as a reference part (as predicted by Marr & Nishihara, 1978, and others). The results of these experiments also suggest the appearance of support serves a similar function, with supporting parts serving as reference points relative to which supported parts are represented. The findings of all three experiments suggest that connectedness plays a role in the integration (binding) of an object’s parts with their spatial relations.

Experiment 4

An alternative account of the connectedness effect observed in Experiments 1–3 is that it may simply reflect the presence of local features (such as cusps) produced where the parts of connected objects meet. In the Part 1-relation condition of all three experiments, the cusps were sufficient to distinguish target-present and target-absent pairs (see Figure 1; although no such differences existed in either the Part 2-relation or Part 1–Part 2 pairs). Because cusps would carry little or no information in the separated condition (as their perceptual availability would be attenuated or eliminated), sensitivity to these cusps may at least partially explain why performance was better with connected than with separated stimuli.

The cusp hypothesis cannot explain all the results of Experiment 1–3 because cusps do not vary with—and therefore cannot explain the effects of—relative size (or support). However, it is possible that the availability of cusps served as an important cue on one third of the connected trials (i.e., Part 1-relation trials) in all these experiments. One purpose of Experiment 4 was to test the role of cusps in the connectedness effect. In this experiment, the two Part 1 shapes were identical at the points where they touched Part 2, making it impossible to distinguish targets from distractors on the basis of cusps in any condition. To the extent that the effects observed in the previous experiments reflected the diagnosticity of cusps on connected Part 1-relation trials, the connectedness effect would be attenuated in this experiment. In this experiment we also tested whether the connectedness effect stems from errors in participants’ memory for the target pictures (rather than perceptual process). Participants viewed the target pictures more often in this experiment than in the previous experiments. If memory errors contributed to the effects observed in the previous experiments, then those effects will be reduced in this experiment.

Method

Participants

Twenty-four undergraduates at the UCLA participated for credit in introductory psychology courses. All had normal or corrected-to-normal vision.

Materials

Figure 10 shows examples of the stimuli. Part 2 was the same shape and size as in Experiment 2, but Part 1 changed so that the two shapes produced identical cusps at their connection with Part 2. One Part 1 shape was curved, and the other was a polygon. As in Experiment 1, Parts 1 and 2 were approximately equal sizes. In the connected stimuli, the curved Part 1 was 2.1 cm (0.8°) X 2.0 cm (0.8°), the polygonal Part 1 was 2.2 cm (0.8°) X 3.2 cm (1.2°), the horizontal Part 2 was 2.5 cm (0.9°) X 1.8 cm (0.7°), and the vertical Part 2 was 1.5 cm (0.6°) X 2.5 cm (0.9°). The complete objects were thus 0.8°–1.7° high and 0.8°–2.1° wide. Separated stimuli were created in the same way as in Experiments 1 and 2. The gap between the parts of the separated stimuli subtended approximately 0.2° of visual angle.

Procedure

The procedure was identical to that used in Experiment 1 except that participants viewed the target pictures every 4 trials instead of every 6 trials.

Figure 10. Critical items used in Experiment 4.
Results

Exposure Duration

On the experimental trials, the mean exposure duration was 206 ms; the minimum and maximum were 159 and 288 ms, respectively. The exposure durations in this experiment were similar to those of Experiment 1 (which used parts of equal size) and longer than those in Experiments 2 and 3 (which used parts of unequal size).

Percentage Correct

The mean percentage of correct responses in the within-subjects conditions is shown in Figure 11. A 2 (connectedness) × 2 (number of fillers) × 3 (conjunction type) MANOVA revealed significant main effects of connectedness, $F(1, 23) = 14.48, p < .001, \text{MSE} = 38.37$, number of fillers, $F(1, 23) = 63.87, p < .0001, \text{MSE} = 58.99$, and conjunction type, Wilk's $\lambda = .313$, exact $F(2, 46) = 24.15, p < .0001$, and a significant interaction between number of fillers and conjunction type, $F(1.55, 35.69) = 18.45, p < .0001, \text{MSE} = 71.60$, with adjusted degrees of freedom. No other interactions were significant. Overall, there were (a) more correct responses on connected trials than on separated trials, (b) more correct responses on 1 filler trials than on 0 filler trials, and (c) in the 0 filler condition, responses were correct most often with Part 1-relation conjunctions and least often with Part 1-Part 2 conjunctions. As shown by the significant interaction between conjunction type and number of fillers, the difference among three conjunction types was significantly reduced in the 1 filler condition. The basic pattern of results was similar to that found in Experiment 1.

False Alarms and Misses

Unlike in the previous experiments, false alarms and misses differed in this experiment. The significant effect of connectedness obtained with the miss scores, $F(1, 23) = 13.63, p < .001, \text{MSE} = 84.20$, but not with false-alarm scores, $F(1, 23) = 1.43, p > .1, \text{MSE} = 122.94$.

Discussion

The results of this experiment clearly show that the connectedness effect was not due to the availability of cusps. In this experiment, the cusps contained no information for distinguishing targets from distractors, but there was still a significant connectedness effect. Importantly, the magnitude of the effect was the same as in the previous experiments, suggesting that the cusps played little or no role in the effects observed in those experiments. The results of this experiment also suggest that the connectedness effect did not simply reflect participants' memory for separated target objects.

FURTHER EXPLORATION OF THE CONNECTEDNESS HYPOTHESIS

As noted in the introduction, image connectedness is neither necessary nor sufficient for inferring physical connect-
edness: Parts that are physically separated in 3-D can appear locally connected in the 2-D image (as when one occludes another), and parts can be connected in 3-D without being connected in 2-D (as when a third surface occludes the join). This fact raises the question of whether image connectedness is necessary or sufficient for the perceptual integration of parts and relations. This question motivated Experiments 5 and 6. In Experiment 7 we addressed a complementary question: Given that connectedness facilitates part–relation integration, will it also facilitate the integration of other object properties? That is, is image connectedness a perceptual constraint on relations specifically or on perceptual integration in general? The results of Experiment 7 suggest that connectedness serves as a constraint on the integration of parts and relations per se rather than a more general constraint on perceptual integration.

Experiments 5 and 6 served another important function as well. In Experiments 1–4, connectedness and proximity were inherently confounded: Connected parts (by definition) were always closer together than separated parts. As such, it is impossible to know whether the results of these experiments reflect the role of connectedness per se or simply proximity. By manipulating perceptual cues other than image connectedness, we examined whether the effects observed in the previous experiments were exclusively due to proximity in Experiments 5 and 6. In these experiments, proximity did not vary across conditions. If proximity was responsible for the connectedness effects observed in the previous experiments, then these effects should disappear in Experiments 5 and 6; if not, then the effects should persist in Experiments 5 and 6.

Experiment 5: Necessity of Image Connectedness

In Experiment 5 we examined whether image connectedness is necessary for the facilitatory effects of connectedness observed in Experiments 1–4. Experiment 5 replaced the connected versus separated distinction with collinearity versus noncollinearity. Here, no target objects contained connected parts. Rather, half the objects (collinear objects, analogous to the connected objects of Experiments 1–4) had parts whose contours were collinear, as if they were connected in 3-D but the join between them was occluded by an invisible surface (see Figure 12). The other objects (noncollinear objects) were similar except that they had no such collinear contours. If image connectedness or proximity is necessary for part–relation integration—and for the connectedness effects observed in the previous experiments—then both conditions in this experiment should resemble the separated conditions of the previous experiments. However, if collinearity can serve as a cue for part–relation integration, then performance in the collinear condition of this experiment should resemble performance in the connected conditions of the previous experiments, and performance in the noncollinear condition should resemble performance in the separated conditions. Collinearity was not confounded with proximity in this experiment (the parts were equidistant across conditions), so no differences in performance between the collinear and noncollinear conditions can be attributed to the role of proximity.

Method

Participants

Sixteen undergraduates at the UCLA participated for credit in introductory psychology courses. All had normal or corrected-to-normal vision.

Materials

The stimuli in this experiment were all light green. The filler items were the same shapes as in the previous experiments. Figure 12 shows the critical items used in this experiment. All had locally separated parts. Each part had two protrusions. Each Part 1 had protrusions at the bottom and left, and each Part 2 had protrusions at the top and right. As in the previous experiments, Part 1 was either above or to the right of Part 2. We manipulated collinearity by manipulating whether the ends of the protrusions were flattened (see Figure 12A) or rounded (see Figure 12B). In collinear stimuli, the parts' flattened protrusions were aligned so that their bounding contours were collinear (as if the protrusions were the visible ends of a single connection occluded by a surface). As shown in Figure 12, two short white line segments were added to the collinear ends of the flattened protrusions, converting the L vertices into V vertices at the points of collinearity. (A pilot experiment revealed that the effect of grouping over L vertices was, not surprisingly, weak.) These line segments were placed at the same positions in noncollinear stimuli. We created noncollinear stimuli by aligning the parts' rounded protrusions (which have no collinear contours). The objects were 0.8°–1.9° high and 0.9°–2.0° wide. The gap between any two parts subtended approximately 0.1°.

Procedure

The procedure was the same as that used in Experiment 4, except that the 1 filler condition was eliminated (i.e., critical items were always presented consecutively as in the 0 filler conditions of the previous experiments), and participants made target detection judgments without confidence ratings. The number of trials was the same as in the previous experiments.

Results

Exposure Duration

The mean exposure duration on the experimental trials was 239 ms; the minimum and maximum were 169 and 321 ms, respectively. The longer exposure durations likely reflected the fact that all trials were 0 filler trials in this experiment.

Percentage Correct

The mean percentage of correct responses in the within-participants conditions is shown in Figure 13. A 2 (connectedness) × 3 (conjunction type) MANOVA revealed significant main effects of collinearity, $F(1, 15) = 30.38, p < .0001$, $MSE = 26.72$, and conjunction type, Wilks's $\lambda = .422$, exact $F(2, 14) = 9.59, p < .005$. The interaction between collinearity and conjunction type was not signifi-
Experiment 6: Sufficiency of Image Connectedness

Experiment 5 showed that image connectedness was not necessary for facilitatory effects on part–relation integration in target detection. In Experiment 6 we examined whether image connectedness would be sufficient for these effects. If two parts are locally connected, is it possible to add additional cues to further facilitate part–relation integration, or are connected parts fully grouped in the sense that no additional cues can further facilitate their perceptual status as parts of the same object? To address this question, in Experiment 6 we held image connectedness constant but manipulated whether an object's parts were coplanar or occluding. (The stimuli in this experiment were 2-D drawings of opaque 3-D objects, making it possible to manipulate the apparent depth and occlusion relations among an object's parts; see Figure 14.) The idea behind this manipulation was that parts that are connected due to an occlusion relation may group less strongly than parts that are both connected and coplanar. If so, then we should observe a coplanarity effect analogous to the connectedness and collinearity effects.
observed in the previous experiments. Alternatively, if connectedness (or collinearity) is sufficient for complete part-relation integration, then we should observe no effects of coplanarity.

Method

Participants

Twenty-four undergraduates at the UCLA participated for credit in introductory psychology courses. All had normal or corrected-to-normal vision.

Materials

All the stimuli, both critical and filler items, were filled line drawings of 3-D objects. The parts had the same shapes as in the previous experiments except that they were depicted as extending in depth (see Figure 14). The faces of the parts were blue or red; the sides of a part were a lighter shade of the same color to make the 3-D structure apparent. The relations between the parts were the same as in the previous experiments. The two grouping conditions (analogous to connected vs. separated) were defined as follows: Coplanar objects (analogous to connected objects) were created by depicting Parts 1 and 2 at the same depth, so that their faces made the same 2-D shape as in the previous experiments. These objects looked as if Part 1 was connected to the top or side of Part 2.

Occluded objects were created by bringing Part 2 in front of Part 1, so that Part 1 appeared occluded behind Part 2. The only difference between corresponding coplanar and occluded objects was whether a small portion of Part 2 was occluded by Part 1 (a coplanar object) or a small portion of Part 1 was occluded by Part 2 (an occluded object). The total area covered by an object was exactly the same across the two conditions. The complete objects were 0.8°–2.0° high and 1.3°–2.1° wide. Filler objects were also of two types: coplanar and occluded. These items were created in exactly the same way as the critical items. Coplanar fillers were used only with coplanar critical objects, and occluded fillers were used only with occluded critical objects.

Procedure

The procedure was identical to that used in Experiment 5.

Results

Exposure Duration

The mean exposure duration on the experimental trials was 220 ms; the minimum and maximum were 159 and 291 ms, respectively.
**Percentage Correct**

The mean percentage of correct responses in the within-participants conditions is shown in Figure 15. A 2 (coplanarity) × 3 (conjunction type) MANOVA revealed significant main effects of coplanarity, \( F(1, 23) = 7.00, p < .025, \) \( MSE = 32.58, \) and conjunction type, Wilks's \( \lambda = .349, \) exact \( F(2, 22) = 20.49, p < .0001. \) The interaction between connectedness and conjunction type was not significant, Wilks's \( \lambda = .895, \) exact \( F(2, 22) = 1.29, p > .3. \) The overall pattern of results was similar to that found in Experiment 5, although the effect of coplanarity was weaker than the effect of collinearity.

**False Alarms and Misses**

Unlike in the previous experiments, false alarms and misses showed different patterns in this experiment. The significant effect of coplanarity was found only with false alarms, \( F(1, 23) = 8.01, p < .01, \) \( MSE = 69.61; \) the misses failed to reach significance, \( F(1, 23) = 0.83, p > .1, \) \( MSE = 52.58. \)

**Discussion**

The results of Experiment 6 were similar to those of Experiment 5, although the effect of coplanarity was weaker than the effects of connectedness and collinearity. In terms of false alarms (but not misses), target detection was better for coplanar than occluded objects, even though all the objects were image connected. This effect suggests that image connectedness is not sufficient for full part–relation integration. Connected parts may be integrated to greater or lesser degrees depending on the other properties of their configuration.

**Experiment 7**

Our purpose in these experiments was to investigate the role of connectedness (and other grouping cues) in the perceptual integration of an object's parts with their spatial relations, and the results suggest that grouping cues serve as a basis for part–relation integration. However, the results are also consistent with the hypothesis that grouping cues simply play a role in perceptual integration in general: Although part–relation integration has been our dependent measure, Experiments 1–6 provided no basis for deciding whether cues such as connectedness play a role in the integration of parts and relations per se or simply in perceptual integration broadly defined.

A review of the literature suggests that our effects may be specific to part–relation integration. In contrast to our results, which suggest that perceptual grouping facilitates part–relation integration, numerous studies have shown that grouping may actually impede certain other kinds of integration. Feature misbinding (e.g., incorrectly binding two spatially separate lines into a single cross or incorrectly binding the color of one object to the shape of another) is more likely within perceptual groups than between perceptual groups (Prinzmetal, 1981; Prinzmetal & Millis-Wright, 1984; Prinzmetal & Keysar, 1989; Prinzmetal, Treiman, & Rho, 1986; Treisman, 1982). It is possible that feature binding and part–relation integration obey different perceptual constraints, with the result that the former is impeded by perceptual grouping (at least as measured by participants' ability to keep features perceptually separate), whereas the latter is facilitated by it. Indeed, this hypothesis is suggested by the differences between the problem of grouping of features into parts and the problem of grouping of parts into objects (as detailed in the introduction). If this hypothesis is correct, then it would explain why our findings differ from those in the literature, and it would also suggest that our findings are specific to the integration of parts with their relations.

However, all the previous studies of which we are aware have used spatial visual search tasks, whereas the experiments reported here used temporal search. It is possible that our results differ from those in the literature, not because feature integration differs from part–relation integration but because spatial search differs from temporal search. It is therefore important to know whether connectedness facilitates the integration of other stimulus properties, such as shape and color, under the temporal search paradigm. If it does, then this would suggest that our results differ from the literature simply because of our experimental paradigm. In turn, it would cast doubt on the suggestion that our results
speak specifically to the role of perceptual grouping in part-relation integration. However, if connectedness does not facilitate shape-color integration, even in a temporal search task, then this would suggest that our results differ from those in the literature because part-relation integration differs from feature integration. In Experiment 7 we investigated whether connectedness would facilitate shape-color integration in the temporal search paradigm.

**Method**

**Participants**

Twenty-four undergraduates at the UCLA participated for credit in introductory psychology courses. All had normal or corrected-to-normal visual acuity and normal color vision.

**Materials**

**Stimuli.** The critical items (see Figure 16) were defined by the shapes and colors of Parts 1 and 2. The spatial relation between the parts was fixed to “beside.” In half the stimuli, Part 1 was blue and Part 2 was red (blue and red stimuli), as in the previous experiments. In the other half (red and blue stimuli), Part 1 was red and Part 2 was blue. The connected stimuli had the same shapes as the connected stimuli with the beside relation in Experiment 1. To equate the visibility of the parts’ colors in the connected and separated stimuli, separated objects had the same overall area as the corresponding connected objects. As a result, the separated objects were slightly more elongated vertically than the connected objects. Corresponding separated and connected stimuli were equal in width. The gap between separated parts subtended approximately 0.1° of visual angle. All the filler items were black. They had the same shapes as the fillers in Experiment 1.

**RSVP sequence.** RSVP sequences were formed in the same way as the previous experiments, except that color assignment, rather than spatial relations, was used to select the critical items. Thus, the three conjunction conditions were Part 1-color, Part 2-color, and Part 1–Part 2 (rather than Part 1–relation, Part 2–relation, and Part 1–Part 2).

**Procedure**

The procedure was identical to that used in Experiment 4.

**Results**

**Exposure Duration**

The mean exposure duration on the experimental trials was 201 ms; the minimum and maximum were 170 and 261
ms, respectively. These values were comparable to those found in Experiments 1 and 4, suggesting that the task difficulty was about the same as in those experiments.

**Percentage Correct**

The mean percentage of correct responses in the within-subjects conditions is shown in Figure 17. A 2 (connectedness) × 2 (number of fillers) × 3 (conjunction type) MANOVA revealed a significant main effect of number of fillers, $F(1, 23) = 138.23, p < .0001$, $MSE = 66.32$, and a significant interaction between number of fillers and conjunction type, Wilks's $\lambda = .611$, exact $F(2, 22) = 6.99, p < .005$. As in the previous experiments, performance was better in the 1 filler than in the 0 filler condition. The interaction between number of fillers and conjunction type reflects the fact that the effect of number of fillers was larger in the Part 1–color condition than in the other two conditions. No other main effects or interactions were statistically significant: $F(1, 23) = 0.06$, for the main effect of connectedness, $F(2, 22) = 1.21$, for the main effect of conjunction type, $F(2, 22) = 0.85$, for the interaction of connectedness and conjunction type, $F(1, 23) = 0.40$, for the interaction of connectedness and number of fillers, and $F(2, 22) = 0.89$, for the three-way interaction. Importantly, no effects related to connectedness approached significance.

**False Alarms and Misses**

As shown in Table 3, neither false-alarm nor miss rates showed a significant effect of connectedness ($F < 1$).

**Discussion**

This experiment revealed no effect of connectedness on observers' ability to integrate shapes and colors in a temporal search task. Importantly, it did replicate some other effects observed with the part–relation integration task, such as the effect of the number of fillers and the interaction between number of fillers and conjunction type. As such, it is unlikely that the failure to observe a connectedness effect simply reflects a weakness of the stimuli or the experimental paradigm. Rather, the lack of connectedness effect in the part–color task suggests that the connectedness effects observed in the previous experiments specifically reflect the role of connectedness (and other grouping cues) in the integration of an object's parts with their spatial relations. However, although connectedness provided no benefit in shape–color integration, neither did it result in a detriment: This experiment did not replicate the between-groups advantage observed by Prinzmetal and others. This discrepancy may reflect differences in the experimental paradigms or stimuli, or it may speak to the manner in which connectedness functions as a cue for perceptual integration. If part connectedness serves primarily as a cue for the integration of parts and relations, then it may have little or no impact on the integration of other features, such as shape and color.

**GENERAL DISCUSSION**

The results of seven experiments reveal that connectedness and other grouping cues facilitated the integration of parts with their relations in shape perception. Four experiments using a temporal search task showed that targets defined by the shapes and relative locations of two parts were easier to detect (and discriminate from distractors) when the parts were locally connected in the 2-D image than when they were spatially separated. These findings cannot be explained in terms of the local emergent features (cusps) created where the parts touched. Even when these features carried absolutely no information to distinguish targets from distractors, participants were still better able to detect connected targets than separated targets (Experiment 4).

The pattern of effects also depended on the specific characteristics of the objects, suggesting that it cannot be explained simply by assuming that a connected stimulus was treated as a single object, whereas a separated stimulus was treated as two objects. Experiments 1, 2, and 3 showed that the pattern of connectedness effects depended on the relative
sizes and support relations of an object's parts. Experiment 1, which used objects whose parts were equal in size, showed a connectedness advantage with all three conjunction types. In the Small 1 condition of Experiment 2, Part 1 was smaller than Part 2; under these conditions, connectedness had a larger effect on participants' ability to integrate Part 1 with its relation to Part 2 than vice versa. In Experiment 3, the opposite-size relations held between Parts 1 and 2 (i.e., and there was no "supporting" relation), and the opposite pattern obtained.

Experiments 5 and 6 showed that image connectedness was neither necessary nor sufficient to produce effects suggesting differences in the perceptual integration of parts with their relations. Experiment 5 showed that even spatially separated parts could be integrated depending on whether they had collinear contours suggesting grouping behind an invisible occluder: Image connectedness was not necessary for part-relation integration. Experiment 6 showed that integration could vary even when an object's parts were connected: Image connectedness was not sufficient for complete part-relation integration. These results suggest that image connectedness is only one of several cues the visual system uses to integrate parts and relations for object recognition. Importantly, both these experiments revealed that proximity was not the only factor responsible for the integration advantage, suggesting that the connectedness effects observed in Experiments 1-4 also were at least partly due to connectedness, not proximity.

Finally, Experiment 7 showed that connectedness did not simply aid perceptual integration in general but may specifically affect part-relation integration. This experiment tested participants' ability to detect targets defined by part-color conjunctions (rather than part-relation conjunctions). Although it replicated some of the effects observed with the part-relation detection task (e.g., the effects of the number of fillers intervening between distractor pairs), it showed no effects of connectedness on part-color integration.

Together, these results strongly suggest that the perception of within-objects spatial relations differs from the perception of between-objects spatial relations. This finding extends those of Baylis and Driver (1993), Baylis (1994), Elder and Zucker (1993), and others. Those studies addressed the ways in which the representation and processing of local features differed as a function of whether those features belonged to the same part or different parts. In the experiments reported here, we required participants to detect objects composed of multiple parts. We found that grouping cues such as connectedness could affect their ability to integrate an object's parts with their spatial relations. These results help to underscore how the grouping of features into parts differs from the grouping of parts and relations into objects. Both problems relate to the issue of complexity—and how the visual system reduces it—in pattern perception. Previous work has suggested that the visual system may solve this problem partly by grouping local elements into convex parts. Our findings suggest that the visual system further groups parts into object-based sets on the basis of image connectedness, collinearity, and coplanarity. This finding is important in the context of structural description theories of object recognition. An important problem for such theories is the rate at which the number of potential part-to-part relations grows with the number of parts in an image. An efficient basis for pruning relations before recognition would make the computational task of structural description much less daunting. Our results suggest that visual cues suggesting physical connectedness (e.g., image connectedness, collinearity, and coplanarity) may serve as one basis for this type of pruning.

Asymmetrical Relations

Among the most interesting findings from these experiments is that the representation of spatial relations appears to be asymmetrical, at least in some circumstances. The effects of relative size and support on the pattern of connectedness effects suggest that the visual system may represent the location of a smaller or supported part relative to a larger or supporting part, but not vice versa (as anticipated by Marr & Nishihara, 1978). Especially in the case of objects with many parts, asymmetrical representations of this type may serve the useful purpose of reducing the number of relations that need to be computed and explicitly coded. Additional tests of the asymmetric relations hypothesis are necessary, but the possibility that relations are represented asymmetrically is an intriguing one with potentially important implications for the representation of object shape.

How Do Within- and Between-Objects Relations Differ?

Our results suggest that the human visual system treats within- and between-objects relations differently for shape perception. An important question concerns whether this difference is one of strength or kind: Are between-objects relations simply "weaker" than within-objects relations, or are they represented in a qualitatively different way? There is reason to hypothesize that the latter may be the case. Numerous findings in neuroscience suggest that the visual system is divided into two relatively independent processing pathways, one specialized to process object identity (the "what" pathway, which goes ventrally from area V1 to the inferotemporal cortex) and one specialized to process spatial information (the "where" pathway, which runs dorsally from V1 toward the parietal cortex; Mishkin, Ungerleider, & Macko, 1983). These pathways—and the visual functions they serve—require different kinds of information about the way objects and parts are arrayed in the world (see, e.g., Goodale, Milner, Jakobson, & Carey, 1991; Mishkin et al., 1983).

One intuitive difference concerns the role of viewpoint. Object recognition (a ventral function) does not require knowledge of where objects are located relative to the viewer (indeed, if possible, it is better to ignore such information for the purposes of recognition). By contrast, navigation and motor interaction (dorsal functions) require precise information about how objects and surfaces are arrayed relative to the viewer. A second potential difference concerns the importance of the within- vs. between-objects
distinction. As discussed previously, the routines responsible for object identification need to know the difference between within- and between-objects relations. The routines responsible for navigation and motor interaction may have much less need for this information. Together, these considerations suggest a possible interaction between the effects of connectedness and viewpoint: If the ventral pathway pays special attention to within-objects relations (whereas the dorsal pathway does not), and if the ventral pathway represents relations in such a way that discounts variations in viewpoint (which the dorsal pathway does not), then the representation of the within-objects relations (e.g., relations between connected parts) may be more robust to variations in viewpoint than the representation of between-objects relations (e.g., relations between separated parts). Preliminary results from our laboratory suggest that connected parts are represented in a less viewpoint-sensitive format than are separated parts (Saiki & Hummel, 1997).

Part–Relation Integration and Feature Integration

The results of Experiment 7 suggest that image connectedness facilitates part–relation integration specifically, not on feature integration in general. The difference between the results of Experiment 7 and those of Experiments 1–6 may reflect an important difference between relational representations (as required for shape–relation integration) and simple feature binding (as required for shape–color integration). Shape–color integration can be performed simply by detecting and binding two independent properties of a single part (its shape and color). By contrast, constructing a relational representation requires information about multiple parts: To know that Part 1 is, say, above Part 2, it is necessary to know where both parts are located. This asymmetry between shape–color and shape–relation binding may explain why the latter depends on part connectedness (which itself is a kind of dependency between two parts), whereas the former does not. In addition, the color–part assignments in Experiment 7 were mutually exclusive, in the sense that if one part was blue, then the other would be red and vice versa. Therefore, it was not strictly necessary for participants to perceive or encode the colors of both parts. This kind of mutual exclusivity cannot hold in the case of spatial relations, where the location of Part 1 relative to Part 2 is necessarily defined by the locations of both parts.

If this account is correct, then one should observe connectedness effects in any task that requires relational integration (e.g., shape and relative size, shape and relative location, etc.) or—more generally—integration of information over two or more separate object parts. For example, it predicts that shape–color conjunction tasks that require participants to encode colors relationally should result in connectedness effects. Further study is necessary to test this hypothesis.

Further Questions

We have interpreted the effects of image connectedness, collinearity, and coplanarity in the context of these properties as cues suggesting physical connectedness. Consistent with the theoretical considerations presented here and by Palmer and Rock (1994), the differences between the effects of connectedness and effects such as those reported by Prinzmetal (1981) and others suggest that not all grouping principles are created equal. However, it remains an open question whether these effects are related to physical connectedness per se or to more general principles of perceptual grouping. One way to distinguish these possibilities may be to examine the effects of cues, such as common fate (co-motion), that encourage perceptual grouping of otherwise physically separate objects (e.g., in the way birds in flight are grouped into a perceptual unit corresponding to the flock). If connectedness belongs to a general class of such cues, then we should be able to observe analogous effects of co-motion. By contrast, if the effects are related specifically to the visual system’s interest in physical connectedness, then co-motion of separate objects may not aid part–relation integration.

A related question concerns the relationship between element connectedness as used in our research and the principle of segmentation at matched concavities as discussed by Hoffman and Richards (1984). According to Hoffman and Richards’s account, the connected stimuli in our research should be perceptually segmented into separate parts. Having accomplished this segmentation, why should the visual system “undo” it, putting connected parts back together into objects? As numerous researchers (e.g., Biederman, 1987; Hummel & Biederman, 1992; Marr & Nishihara, 1978; Palmer & Rock, 1994) have argued, visual object representations are hierarchical, with both decomposition and integration working in parallel. Matched concavities serve as cues for segmentation of objects into convex parts, and image connectedness serves as a cue for reintegrating those parts into a (structured) representation of a whole, multipart object. Without both of these processes working together, objects could be perceived only as undifferentiated, holistic forms (see Hummel & Biederman, 1992).

Another question concerns the relative contributions of connectedness and proximity in the effects reported here. Experiments 5 and 6 showed that proximity was not the sole determinant of the observed grouping effects, but this does not imply that proximity played no role in the effects (e.g., in Experiments 1–4). Because proximity and connectedness are inherently confounded, the “proximity versus connectedness” question may ultimately prove empirically unanswerable. Instead, it may come down to a matter of parsimony and theoretical emphasis. For example, Palmer and Rock (1994) treated varying degrees of proximity as varying approximations to connectedness. What is more important is the utility of connectedness–proximity as a cue to perceptual grouping: Why does the visual system care about connectedness–proximity, and how does connectedness–proximity affect the processing of a stimulus? The experiments reported here were motivated by a specific answer to the “why” question (to prune the relations in a visual image), and the results suggest a specific answer to the “how” question (by affecting part–relation integration).

Whatever the answer to these questions turns out to be,
the findings presented here suggest that the visual system actively integrates an object's parts with their relations and that perceptual cues suggesting physical connectedness play an important role in this process.

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