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Concept formation and categorization of complex, asymmetric, and impossible figures

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Abstract Impossible figures are striking examples of inconsistencies between global and local perceptual structures, in which the overall spatial configuration of the depicted image does not yield a coherent three-dimensional object. In order to investigate whether structural "impossibility" is an important perceptual property of depicted objects, we used a category formation task in which subjects were asked to divide pictures of shapes into groups that seemed most natural to them. Category formation is usually unidimensional, such that sorting is dominated by a single perceptual property, so this task can serve as a measure of which dimensions are most salient. In Experiment 1, subjects received sets of 12 line drawings consisting of six possible and six impossible objects. Very few subjects grouped the figures by impossibility on the first try, and only half did so after multiple attempts at sorting. In Experiment 2, we investigated other global properties of figures: symmetry and complexity. Subjects readily sorted objects by complexity, but seldom by symmetry. In Experiment 3, subjects were asked to draw each of the figures before sorting them, which had only a minimal effect on categorization. Finally, in Experiment 4, subjects were explicitly instructed to divide the shapes by symmetry or impossibility. Performance on this task was perfect for symmetry, but not for impossibility. Although global properties of figures seem extremely important to our perception, the results suggest that some of these cues are not immediately obvious or salient for most observers.

Keywords 2-D, 3-D · Shape perception · Object recognition · Impossible figures · Categorization · Concept formation

Artists, mathematicians, scientists, and philosophers have long pondered the nature of the mechanisms underlying our ability to detect and integrate the numerous bits of visual information that ultimately give way to a perception of structural coherence, or lack thereof. The mature visual system may be specially tuned for processing objects, both real and depicted, in a globally coherent three-dimensional (3-D) fashion. This remarkable capacity enables us to readily recognize and classify a myriad of patterns and shapes. The perception of global 3-D shape arises from the extraction of critical contour information and the spatial integration of local lines, junctions, edges, and other surface characteristics (Biederman, 1987; Biederman & Ju, 1988; Marr & Nishihara, 1978).

The perception of 3-D structure is saliently illustrated by the case of impossible figures. Human observers generally respond differently toward, and show increased interest in, pictures of impossible objects, and these observations have further illuminated the nature of visual processing and object representations. When looking at an image, the visual system needs to ascertain whether all of the parts add up to a globally coherent whole. Impossible figures (like those shown in Fig. 1a) tend to attract our attention and pique our interest for extended periods of time, as we try to resolve the components. Each part of an impossible figure in isolation is locally possible, but the adjoining parts do not yield a coherent real object—that is, it cannot be rendered in three dimensions out

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of solid, continuous material.[1] The apparent differences between possible and impossible shapes are generally assumed to be quite obvious and noticeable among sighted people, yet little is known about our conceptual understanding of such objects. For this reason, impossible objects provide an interesting way of investigating the nature of coherent object representations, as well as the conceptual understanding of structural possibility versus impossibility.

Recent studies have shown that young infants can differentiate between possible and impossible figures, an ability that requires analyzing local pictorial depth information and integrating the global spatial relations that lead to perceiving coherent 3-D objects. For example, 4-month-old infants looked longer at pictures of impossible cubes relative to possible ones (Shuwairi, 2009; Shuwairi, Albert, & Johnson, 2007), and they more actively scanned the anomalous region of the impossible cubes (Shuwairi & Johnson, 2013a, b). Another study with 9-month-olds revealed that older infants engaged in a greater frequency of manual exploration, social referencing, and babbling when they interacted with a color photo of the impossible cube relative to the possible one and other control displays (Shuwairi, Tran, DeLoache, & Johnson, 2010). This research consistently revealed an early capacity to detect differences in global shape on the basis of the local pictorial information present in static images. Young infants readily detect these critical differences and also appear curious about the novel geometry found in impossible object displays. However, such findings leave open the question of how and when we arrive at a conceptual understanding of objects as globally coherent, logically formed, and structurally sound in three dimensions.

Computational vision studies with adults suggest that a number of low-level perceptual properties are used to identify figures as impossible, including edge and vertex information, surface parity, and number of "twists," followed by a serial analysis of local relative depth cues and the spatial relations among parts (Cowan & Pringle, 1978; Cowie & Perrott, 1993; Donnelly, Found, & Müller, 1999; Enns, 1992; Enns & Rensink, 1991; Sugihara, 1982). Other work has focused on mnemonic processes involved in recognizing possibility (Cooper & Schacter, 1992; Schacter, Cooper, & Delaney, 1990; Schacter, Cooper, Delaney, Peterson, & Tharan, 1991). These researchers postulate that a structural description system (SDS) encodes and represents exclusively 3-D, globally coherent, structurally "possible" objects, and does not process shapes with inconsistent or illogical spatial arrangements of lines and surfaces. Since the impossible figures lack global coherence, the SDS does not encode their structure, and therefore perceptual priming for this particular category of shapes does not occur (Cooper & Schacter, 1992; Schacter et al., 1990; Schacter et al., 1991).

In the familiarization phase of Cooper, Schacter, and colleagues' perceptual-priming paradigm, observers viewed a series of rapidly presented line drawings (shown for 100 ms each), half of which were possible and half impossible, and they judged whether each figure was facing to the left or right. In the test phase, observers judged whether each shape was possible or impossible. Half of the test images were previously viewed during the study phase and half were novel. Priming, in the form of increased accuracy and/or decreased reaction time, was reliably obtained among college-age subjects, but only for the previously seen possible figures, whereas a negative-priming effect emerged for the impossible ones.

That observers were consistently worse on judgments involving previously seen or *familiar* impossible figures was an interesting effect indeed. Ratcliff and McKoon (1995) claimed that a familiarity bias inclines observers to respond "possible" when they see stimulus information that looks familiar, even local parts of a previously viewed impossible figure. They proposed that this could be driving the negative-priming effect for previously studied impossible figures.

Research has continued to examine the perceptual mechanisms underlying this interesting pattern of results. Subsequent work has called into question the extent to which priming for possible shapes rather than impossible ones may be driven by other global properties, such as symmetry and figural complexity, which may underlie performance differences in these tasks (Carrasco & Seamon, 1996; Liu & Cooper, 2001; Soldan, Hilton, Cooper, & Stern, 2009). Asymmetric objects present a quandary because they are *possible* and have coherent structures and yet did not show significant priming. For example, when the classic priming task was repeated using only possible figures that were either symmetric or asymmetric, priming was more robustly observed in the symmetric shapes (Liu & Cooper, 2001; Soldan et al., 2009). Although this could reflect the bias that Ratcliff and McKoon (1995) suggest, it could also reflect greater ability to form representations in memory of the simpler and more coherent figures.

Structural coherence is not the only property necessary to produce priming, and more specifically, symmetry may be a particularly compelling dimension and possible indicator of whether global shape is ultimately encoded and represented by the SDS. In addition, Carrasco and Seamon (1996) suggested that figural complexity might play an important role in representing shape, rather than possibility per se. They found that subjects' ratings of object complexity were higher for impossible objects than possible objects. When complexity was equated between possible and impossible objects by

[1] In a few well-known cases, people have actually constructed objects that look like impossible images (e.g., Sugihara, 2008; Zaidi, 2005). However, those objects only resemble the picture when viewed from a particular angle, and they often contain (unseen) gaps. Most importantly, observers do not generally perceive pictures of impossible figures as depicting those objects, but instead report that the object cannot exist as shown.

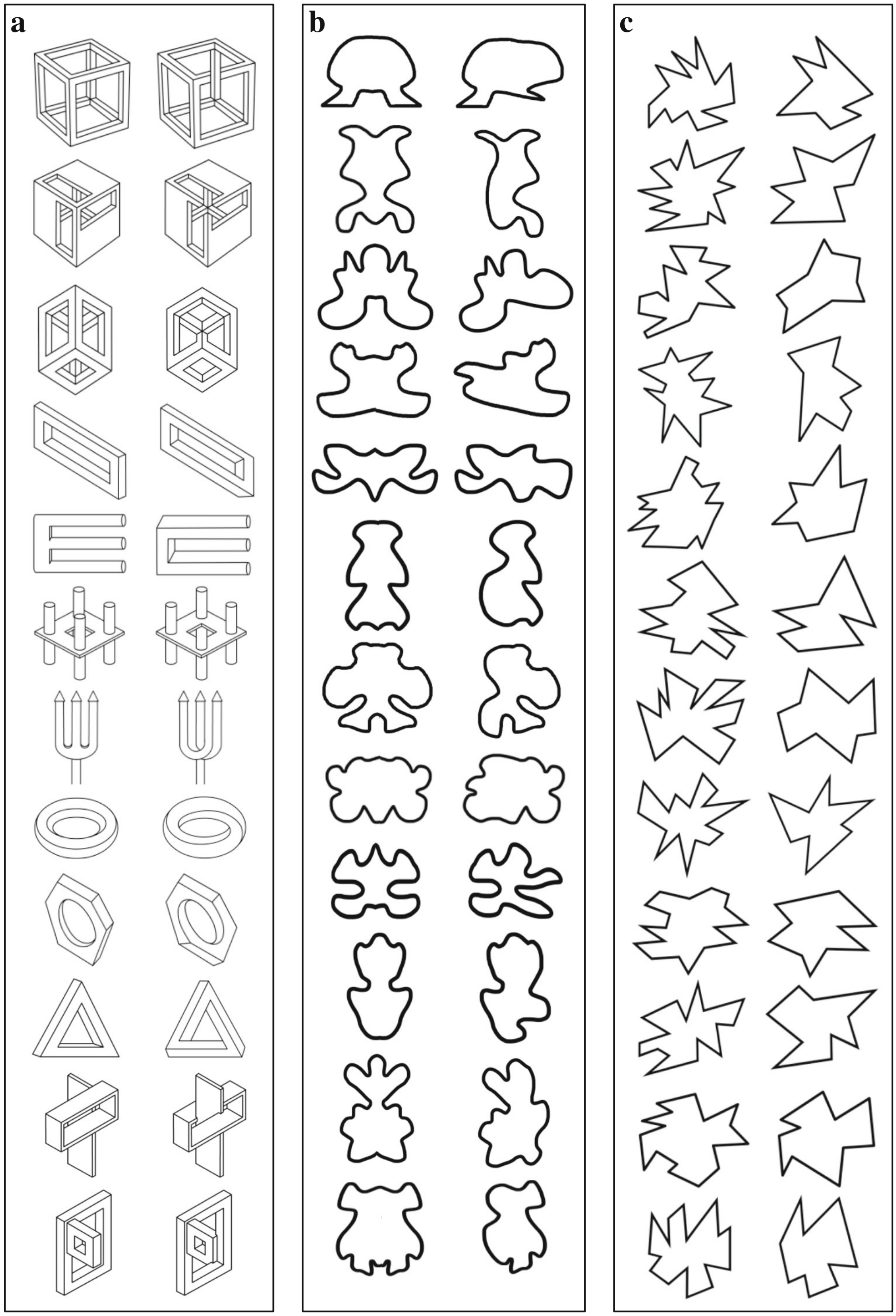

Fig. 1 Examples of visual stimuli used in the sorting tasks: (**a**) *possible* and *impossible* figures, (**b**) *symmetric* and *asymmetric* figures, and (**c**) *complex* and *simple* shapes

using impossible objects with lower complexity scores, both types of objects showed priming in the classic object decision task. Taken together, these findings suggest that our internal mental representation system (i.e., the SDS) is sensitive to a number of global properties of shape that, in addition to global coherence, also include the dimensions of symmetry and stimulus complexity. However, the exact interplay of global pictorial variables is still not fully understood.

This research suggests that aspects of structural complexity and coherence are important to perceiving and representing depicted objects. However, conceptual understanding of these geometric properties has been little investigated, and questions remain about the nature of our conceptual understanding of 3-D objects. For example, do people spontaneously identify drawings as being symmetrical or impossible? And, do they see these properties as being important features of the depicted objects? Categorization tasks have been used to examine how people identify and classify together distinct entities, and we draw on this field to investigate people's thinking about figures. Here, we used a series of category formation tasks to evaluate whether stimulus features such as *impossibility*, *symmetry*, and *complexity* are significant features for identifying and classifying objects.

Category formation

The most familiar task in the experimental study of categories is the *category-learning* task first devised by Hull (1920). In that task, the experimenter designs two or more categories with different names (or associated with different responses), which subjects attempt to learn. By contrast, *category formation* is a very different task, in which numerous items are presented simultaneously to subjects. After examining them, the subject is asked to divide the items into the groups that seem "best or most natural" (Medin, Wattenmaker, & Hampson, 1987). This instruction provides a suggestion that the groupings should not be completely arbitrary, without specifying any particular basis for their separation.

Initial studies of the category formation task yielded very surprising results. Whereas real categories generally group together items that are globally similar, with many properties in common, when people are asked to form their own categories, they consistently form groups defined by one critical feature (Ahn & Medin, 1992; Medin et al., 1987). For example, imagine that the stimuli are pictures of cartoon bugs that could be separated into two family-resemblance categories whose members have five or six features—but not all features—in common (cf. Rosch, 1973; Rosch & Mervis, 1975). Rather than identify those categories, people tend to choose one stimulus dimension, such as the presence of antennae or the number of legs, and then divide the items into two groups: antennae versus no antennae, or four versus six legs. The exact stimulus dimension used for this division can vary across subjects and informally seems to depend on perceptual salience or conceptual importance (e.g., some subjects will point out that number of legs defines insect categories).

The finding of one-dimensional sorting is extremely consistent, at least in the North American university population. Attempts to discourage such sorting generally fail. For example, if no features can be used to sort every item, subjects may use one feature to do an initial sort, and then choose another one to sort the remaining items—that is, two one-dimensional sorts (Ahn & Medin, 1992). Using holistic stimuli caused people to attempt to impose a dimensional structure on the stimuli to use as a one-dimensional sort (Regehr & Brooks, 1995).

These results have interesting implications for understanding the nature of categories (see Lassaline & Murphy, 1996; Murphy, 2002; Spalding & Murphy, 1996). What is relevant here is that the category formation task can provide a measure of what property of complex stimuli seems to be most important in identifying the stimulus. That is, if number of legs seems to be the most critical dimension in separating insects, then that will be chosen by many people as the basis for their one-dimensional sorts.

For the present experiments, we used the category formation task to investigate people's perception and understanding of impossible figures and other geometric properties of objects. However, unlike studies that have examined the perceptual consequences of different properties and cues, in our study we considered people's conscious thoughts about such properties. That is, do they explicitly notice a perceptual property sufficiently to use it as a basis for category formation? It seems intuitive that the difference between possible and impossible figures is obvious, because they result in things that either could or could not actually exist. This is not a subtle or inconsequential property. A drawing created with contradictory spatial relations that seemingly depicts something that cannot exist (under normal viewing conditions and assumptions) should appear to be very different from a depiction of a coherent 3-D object. Other perceptual judgments about configural differences between drawings, such as angular versus rounded edges, simple versus complex, or left versus right orientation seem inconsequential in comparison to the dimension of impossibility. But will naive observers think the same way?

The category formation task is an interesting measure of attention to impossibility (and other dimensions) because it does *not* directly ask about the dimension, but requires people to spontaneously notice it and put it to use. Thus, this dimension is essentially in competition with other perceptual properties, and the use of the feature will reveal how salient and important it seems, as compared to those other properties. One possibility is that although impossible figures clearly have something wrong with them, they may not seem to form a cohesive class of objects. One figure might be thought of as "missing a line," another as "having an extra part," and a third as being "weird." Although we can theoretically identify the pictures as being similar in not representing 3-D objects, that may not be a dimension that naive observers also spontaneously extract. Of course, they might identify a simpler property, such as "there's something wrong with these" or "these are all kind of weird." Explicitly understanding the nature of impossible objects is not necessary in order to divide up the stimuli that way. Thus, the task provides a lenient measure of noticing that something is wrong in impossible figures.

The present experiments

In order to investigate this issue, we initially constructed pairs of structurally similar possible and impossible objects, based on stimuli used previously by Shuwairi and colleagues (Shuwairi, 2009; Shuwairi et al., 2007; Shuwairi & Johnson, 2013a, b; Shuwairi et al., 2010). (For the sake of clarity, we refer to the possible–impossible difference as the *dimension of impossibility*, because *possibility* has many other senses that could lead to confusion.) The use of paired drawings allows some degree of stimulus control over other properties that might be correlated with the impossibility dimension. However, pilot work showed that some subjects tended to group together the pairs of items (e.g., the possible and impossible trident, the possible and impossible ring, etc.). Because the category formation task puts no limits on the number or size of categories, this is a reasonable response. Of course, one could change the instructions to permit only two categories, but this would amount to preventing people from using their preferred sorting strategy. Therefore, we attempted to measure this tendency rather than eliminate it, by creating different conditions in which such pairs of items were presented together or not (see the Exp. 1 Method section for details). Thus, the tendency to form similar pairs of items was (in one condition) pitted against the use of impossibility as a basis for sorting.

Although (im)possibility is of course an important aspect of a depiction of a putative 3-D object, other global properties of depictions do not require as much perceptual analysis, such as figure complexity and symmetry. In Experiments 2, 3, and 4, we examined these dimensions as bases for category formation, to compare their availability and salience in conscious grouping decisions. Although the concept of an impossible figure may be unfamiliar to naive subjects, we anticipated that they could surely notice and identify the presence of symmetry.

Assuming that perception of these global properties is simple and that the properties are salient, we would expect that most observers should notice and use these properties to form categories. If they did not, this would cast doubt on the assumption that impossibility and other global characteristics, such as symmetry and complexity, are indeed salient qualities that people use in thinking about novel shapes.

Experiment 1: Sorting task with possible and impossible figures

In this experiment, we investigated the basic question of whether people would notice and use figure impossibility to form categories. Figures were constructed in pairs (see Fig. 1a), making it plausible to form categories of each pair. Therefore, we contrasted conditions in which those pairs were present to conditions in which only one item of a pair was present (keeping constant the total size of the stimulus set). We gave subjects multiple opportunities to sort the cards. Under the assumption that impossibility is a critical property of any such drawing, people should readily use this as a basis for sorting, although other bases for sorting were also highly likely, such as shape geometry (e.g., straight edges vs. curvy or protruding parts) or similar object pairs, in some conditions. By permitting multiple sorts, we allowed subjects to use any property that they found important as a basis for categorization.

Method

Subjects A group of 24 college undergraduates (17 females, seven males) recruited from courses enrolled in the Psychology Department Subject Pool at a large private urban university in the Northeast participated in the experiment for course credit. Subjects were randomly assigned to each condition, for a total of 12 per condition.

Materials We constructed 24 pictures (12 pairs) of possible and impossible objects using Adobe Flash (see Fig. 1a). Each stimulus image measured approximately 10 × 10 cm. Images were printed on card-stock paper measuring 5 × 4 in. and were individually laminated to protect from repeated handling. Two variations were created for each shape—a possible and an impossible version—which constituted a structurally "matched" pair of images. Some of the objects differed exclusively in a "critical region" that served to make the rest of its global 3-D structure either possible or impossible. Some of the impossible objects did not contain a particular anomalous region, but the configuration of local lines that comprised the depicted object was globally irreconcilable.

We created four sets of images, two for each condition. Each set had 12 of the 24 items, which were distributed so that all stimuli were tested in each condition, and each set included six possible and six impossible objects. In the *paired condition*, the 12 pictures in each set were six pairs of the figures, in which the possible and impossible mates of each figure pair both occurred (e.g., both the possible and the impossible triangle). In the *unpaired condition*, items were assigned such that different members of a given pair did not appear together. For example, in one unpaired set, the possible triangle and the impossible trident might occur; in the other set, the impossible triangle and the possible trident would occur. Thus, subjects could not form possible–impossible pairs in that condition.

Procedure Subjects sat at a table across from the experimenter and were informed that they would be sorting pictures of objects into groups and answering questions about the shapes. Subjects received one of the two sets of images from their assigned condition. These stimuli were shuffled into a stack of comingled images, and subjects were asked to look at all of the images before sorting them into the groups that seemed best or most natural to them. The experimenter observed the free sorting task, and immediately afterward asked the subject to briefly describe the basis of the groups. Subjects continued to sort the images into groups until they did not see any additional way to divide them up that seemed natural. At no point did the experimenter describe the perceptual dimensions being evaluated in the study.

Results

We used a liberal coding of the sorts, which gave credit for using impossibility either if the items were perfectly divided into possible versus impossible sets or if subjects stated that impossibility (or a related property) was the basis for sorting. It was certainly possible to make errors while attempting to sort the figures on their impossibility, and we wished to know whether people readily perceived and used this property—not whether they could detect it perfectly. In Experiment 1, only three possible–impossible sorts had errors (one subject corrected it on the subsequent sort). In all experiments, the errors usually involved one item misgrouped, and never more than two items, so we will ignore such errors from now on.

Paired condition On the first round of sorting in the paired condition, only three subjects sorted by possible versus impossible; one sorted by shape similarity (i.e., square vs. round); and eight of the 12 subjects sorted items into their pairs. On the second round of sorting, five used impossibility, and four used shape similarity (e.g., round vs. straight). Another popular basis for sorting in the second and third attempts was complexity (not related to impossibility), with one subject using it during the second sort and another four in the third. In the third round of sorting, four used complexity, four used shape similarity, and another four gave up after their second sort (11 of 12 gave up after the third sort). In total, four of the 12 subjects never sorted any of the images by impossibility (see Table 1).

Unpaired condition On the first round of sorting in the unpaired condition, ten of 12 subjects grouped by general shape similarity, and two by what they reported as a combination of complexity and impossibility. On the second round, four used impossibility, another five used complexity, two used shape similarity, and one stopped after the first sort. Half of the subjects never used impossibility at all.

In the descriptions of the possible–impossible groupings, subjects varied in how they described the impossible objects. Some of the descriptions included "weird, difficult to comprehend objects," "paradoxical shapes," "pictures that can't exist in 3-D," and "unrealistic shapes." The most common description was "optical illusions." Only one subject used the term "impossible" to describe a group.

Replication of Experiment 1

We replicated the unpaired sorting task with possible and impossible objects at a different institution. The sample included 14 college undergraduates (ten females, four males), who participated in the study for course credit. Only three subjects sorted by possible-impossible: Two did so on the first try with zero errors, and one did so on the second try with one error (although he reported that his sorting was based on other features to form three groups; i.e., cubes and rectangles vs. nonsquares with cylindrical parts vs. optical illusions). The remaining 11 subjects never sorted by impossibility. In the first attempt, nine sorted by general shape similarity (e.g., blocks vs. nonblocks and things with protruding parts), two sorted by complexity, and one sorted by 2-D–3-D properties (e.g., flat/short vs. deep/boxy). In the second attempt, five sorted by shape similarity, three based their sorting scheme on a combination of complexity and 3-D properties, and another three sorted by 2-D–3-D properties (i.e., flat 2-D patterns vs. 3-D objects). Interestingly, however, the groups formed by those individuals who sorted by 2-D–3-D (self-described as "simple and/or 2-D" and "complex and/or 3-D") contained roughly equal numbers of possible and impossible figures. The two subjects who initially sorted by possible–impossible did not sort the figures any further, but stated that they also could have sorted them differently, on the basis of their compositional elements (i.e., square or round parts). (We describe other aspects of these subjects' performance in Exp. 4.)

Discussion

The fact that a drawing depicts a possible 3-D object or one that cannot be readily constructed seems to be a salient and important aspect of the figure. However, in their first sorting attempts, only seven of 38 subjects separated items into possible and impossible figures. Even when given multiple opportunities to re-sort the items, several subjects never formed any categories based on impossibility or a related dimension (e.g., "weird objects"). Surprisingly, figure possibility does not appear to be a dimension that is spontaneously extracted and used very readily, with only 18 % of subjects using it on the first round.

The pairing manipulation did have an effect, although not much of an influence on noticing the dimension of impossibility. When pairs of items were in the sorting set, a majority of subjects initially grouped them into six pairs of items. However, this did not prevent them from seeing the difference between possible and impossible figures. Indeed, by the end of the experiment, eight of them had used that dimension once, about the same as the unpaired condition (six eventually using it). One might have argued that seeing the pairs together could increase the chance of identifying the impossibility dimension, since the two items in the pair were very similar

Table 1 Summary of subjects' sorting strategies in each condition

Condition	Types of Sorting Strategies Observed					
	Possible–Impossible	Symmetric–Asymmetric	Simple–Complex	Matching	Shape Similarity	2-D–3-D
Experiment 1						
First Sorting Attempt						
Paired Possible–Impossible	3	–	–	8	1	–
Unpaired Possible–Impossible	2	–	–		10	–
Replication of Unpaired Possible–Impossible	2	–	2		9	1
Second Sorting Attempt						
Paired Possible–Impossible	5	–	1	1	4	–
Unpaired Possible–Impossible	4	–	5		2	–
Replication of Unpaired Possible–Impossible	1	–	3		5	3
Experiment 2						
First Sorting Attempt						
Symmetric–Asymmetric		2	1		9	–
Simple–Complex		–	10		2	–
Second Sorting Attempt						
Symmetric–Asymmetric		1	–		8	–
Simple–Complex		–	3		4	–
Experiment 3						
First Sorting Attempt After Drawing Task						
Symmetric–Asymmetric		8	–		–	–
Possible–Impossible	3	1	–		8	–
Second Sorting Attempt After Drawing Task						
Symmetric–Asymmetric		1	–		–	–
Possible–Impossible	2	–	–		10	–
First Sorting Attempt (No Drawing)						
Symmetric–Asymmetric		8	–		–	–
Possible–Impossible	3	–	–		9	–
Second Sorting Attempt (No Drawing)						
Symmetric–Asymmetric		–	–		–	–
Possible–Impossible	1	–	–		11	–
Experiment 4						
Instructed Sorting						
Symmetric–Asymmetric		12	–		–	–
Possible-Impossible	12	–	–		–	–
Replication of Possible–Impossible	11	–	–		1	–

Empty cells indicate that a sorting strategy was not available for that stimulus set

except for this property (i.e., creating alignable differences; Markman & Gentner, 1993). However, if such an effect was present, it was obviously very small.

Experiment 2: Sorting task with simple, complex, symmetric, and asymmetric figures

It was surprising that the use of the impossibility dimension of the figures was so weak. Some subjects never used this dimension, and those who did predominantly used it only after prompts of "Is there any other way to divide up the figures?" The difference between the impossible and possible figures was not due to a single pictorial property, but to a complex relation of the parts of the object and their (in)ability to be easily linked into a simple 3-D structure. Was the complexity of this property responsible for its apparent lack of salience, or was it rather the global nature of the property? To investigate this question, we examined the properties of symmetry and object complexity in the same task. These properties do not depend on the presence or absence of a local feature, but instead require recognizing a property of the figure as a whole. Both properties are computationally simpler than that of impossibility, since they do not require any 3-D interpretation. Indeed, the figures all appeared to be 2-D images rather than solid objects. Thus, using this information seems simpler than using impossibility as a dimension. Nonetheless, if global pictorial properties are not salient, subjects may not group items using them.

Our manipulation of complexity was specific to the simple drawings that we used, so it is difficult to draw on past literature to say whether it should be particularly salient. Symmetry, however, is well known to be an important aspect of the shape dimension, at least since the Gestalt psychologists' definition of *good form*. Furthermore, experimental studies have shown that the type of vertical symmetry that we used here is perceptually dominant (Rock & Leamon, 1963) and is quickly identified in reaction time tasks (Palmer & Hemenway, 1978). Thus, although it is a global property, it is one that seems to be readily noticed.

Method

Subjects Another 24 college undergraduates (17 females, seven males) participated in the experiment for course credit. These subjects were randomly assigned to conditions, for a total of 12 per condition.

Materials Two new types of sets, symmetric and asymmetric figures (see Fig. 1b) and simple and complex figures (see Fig. 1c), were created using TweakerSoft VectorDesigner. Both sets included 24 line drawings. The symmetric and asymmetric figures were created by first making 12 asymmetric figures. The 12 new but related symmetric images were generated by cutting the original 12 asymmetric figures in half along the vertical midline. Six left and six right halves were selected from the original 12, which were then duplicated, mirror flipped, and joined together with their mirror image to create a set of 12 symmetric complementary figures. The 24 images were divided into two sets of 12, with each set containing six unique symmetric and six unique asymmetric figures without their respective mates, so that matching on the basis of parts would not be a practical choice for sorting.

The simple and complex figures were created by first making a set of 12 complex figures, each composed of 17 or more line segments. The complementary set of 12 simple figures was generated by deleting vertices from each figure and reconnecting the remaining ones until a figure contained ten or fewer vertices. Although the simple figures might not immediately appear to resemble the complex mates from which they originated, they did share global shape properties. The 24 images were divided into two sets of 12, with each set containing six unique complex and six unique simple figures, without their respective mates, as in the symmetry sets.

Procedure Each subject was assigned to either the symmetric–asymmetric or the simple–complex condition and was given one of the two sets of 12 figures described above. The subject then performed the same free sorting task as in Experiment 1, only using these new items instead of the possible–impossible figures.

Results

In the symmetric–asymmetric condition, two observers sorted by symmetric–asymmetric on the first try, and another one did so on the second try. The remaining ten subjects indicated that they had sorted by size or linear dimensions, roundness of shape, number of grooves or bumps, and other local perceptual features not pertaining to the dimension of symmetry (see Table 1).

In the simple–complex condition, ten subjects sorted by the dimension of simple versus complex on the first try, and another one did so on the third attempt (with one error). The remaining subject grouped the figures on the basis of other local properties of shape.

Discussion

The results were again surprising: Figural complexity appeared readily detectible, and sorting by this property seemed effortless among the vast majority of subjects. On the other hand, although symmetry was a seemingly simple and obvious feature of the visual stimuli, the large majority of subjects did not notice it and use it to form categories. It seems unlikely that they could not identify symmetry, especially since there is ample evidence that subjects respond rapidly and accurately to displays with bilateral symmetry along the vertical midline (Palmer & Hemenway, 1978; Wolfe & Friedman-Hill, 1992). Symmetry is important in Gestalt grouping (e.g., Wertheimer, 1958, p. 130) and can aid in the detection of briefly presented shapes in noise (Machilsen, Pauwels, & Wagemans, 2009). This failure to use symmetry in sorting is especially surprising, given that subjects were very willing to use complexity to sort figures in the other condition (11 of 12 subjects). Although we have presented complexity as a global property of the object, it was also correlated with a local feature—namely, the density of sharp, pointy edges (see Fig. 1b). Conceivably, a feature like "jaggedy" could be identified as a local property of one section of the drawing, rather than requiring a global computation pertaining to the entire shape.

Perhaps more careful study and thinking about the shape is necessary for people to be able to consciously encode and use global features. As we noted above, the computational requirements of interpreting a drawing as a possible or impossible 3-D object seem significant. If people are not studying the items particularly carefully, they also may not be investing much effort in constructing 3-D models of the drawing. Although symmetry is simpler to compute, consciously identifying the stimuli as symmetric or asymmetric may also require more careful study. The visual system may represent a picture's symmetry without the perceiver thinking, "That is symmetric." Or, as Machilsen et al.'s (2009) results suggest, the visual system may be biased to identify symmetric objects, without conscious detection of the symmetry. In Experiment 3 we therefore attempted to ensure that subjects paid close attention to the figures and attempted to interpret them before carrying out the category formation task.

Experiment 3: Drawing pretask

After finding weak use of symmetry and impossibility as bases for sorting figures, we implemented a procedure to attempt to force subjects to attend more closely to the drawings' structure; namely, we asked subjects to sketch a copy of each figure prior to sorting. We hypothesized that creating a hand-drawn image would require observers to attend to the parts of each shape, possibly increasing the chance of noticing their incoherence. That, in turn, would facilitate subjects' ability to sort the pictures into groups on the basis of the dimensions of either structural impossibility or symmetry.

Method

Subjects A group of 48 college undergraduates (13 females, 35 males) participated in the experiment for course credit. Subjects were randomly assigned to each condition, for a total of 24 per condition.

Materials The stimuli were the two sets of unpaired possible and impossible figures from Experiment 1 and the two sets of symmetric and asymmetric figures from Experiment 2.

Procedure In the drawing condition, subjects were given one of the sets of images and asked to draw each figure as best they could on a blank sheet of paper. They were given 10 min to sketch the 12 figures, giving them a little less than 1 min per drawing. Then each subject was asked to sort the 12 images into groups, as in the previous experiments. The subjects then went through the same procedure with another set of figures. In the no-drawing condition, subjects did the two free sorting tasks without first drawing the figures. The ordering of conditions was counterbalanced, such that half of the subjects in each condition did a symmetric–asymmetric set first, followed by a possible–impossible set, and the other half did the reverse ordering. Because of the repeated testing, we only allowed one sort per set.

Results and discussion

After the drawing pretask, ten of the 12 observers sorted successfully on the symmetric–asymmetric task: eight in the first, one in the second, and one in the third round of sorting (see Table 1). And, after drawing, seven of the 12 observers sorted successfully on the possible–impossible task: Three did so in their first attempt, two in the second, and another two in the third round of sorting. Without the drawing pretask, eight of the 12 observers sorted successfully on the symmetric–asymmetric task in their first attempt (the remaining four did not sort by any apparent method), and six of the 12 observers sorted successfully on the possible–impossible task—three in the first attempt, one in the second, and two more in the third. The percentages of subjects who successfully sorted did not differ by performance on the drawing task, $\chi^2(1, N = 48) = 0.82, p = .36$, or stimulus order (i.e., possible–impossible first or symmetric–asymmetric first), $\chi^2(1, N = 48) = 0.09, p = .76$.

Sketching the figures did not facilitate observers' representation of possible and impossible objects, and about half of the subjects did not make categories based on this dimension. However, we obtained more sorting on the basis of symmetry in the present experiment than in Experiment 2 (overall, more than three-quarters of the subjects sorted on symmetry, as compared to only a quarter in Exp. 2). We have no particular explanation for this difference, given that the subjects came from the same pool. If we ignore the drawing condition (which may have had a slight effect), the pooled rate of using symmetry across Experiments 2 and 3 was 46 %. Combining Experiment 3 (without drawing) and Experiment 1 along with the replication (unpaired sets) for the impossibility items, exactly 40 % of subjects used impossibility as a basis for sorting at some point. Overall, then, the rate of using global perceptual properties in category formation seems surprisingly spotty.

Experiment 4: Instructed sorting

The low rates of sorting figures on the basis of impossibility and even symmetry is surprising. Clearly, subjects did not spontaneously identify the figures as possible and impossible or as symmetric and asymmetric, or find these to be important bases on which to group the items. Because we did not require perfect sorting in order to count an attempted sort as using one of these bases, the results cannot be explained by occasional errors in classifying a particular figure. However, we do not know whether people *could* sort on these bases. Perhaps the perception of these properties is simply not very reliable, and therefore they cannot serve as bases for classification.

Schacter et al. (1990) asked subjects to identify individual items as being possible or impossible. When presented quickly (100 ms) on a monitor, the items were classified correctly only about two-thirds of the time. But when the items were printed on white paper and time was unlimited, classification was 95 % accurate (Schacter et al., 1991). Since our task did not have time pressure, we expected that people would be fairly accurate. However, dividing up a set of items is more difficult than classifying individual items, so we tested our own stimuli in a sorting task with direct instructions to sort the items on the basis of impossibility or symmetry, depending on the set.

Although perfect sorting seems unlikely, especially for the possible–impossible items, we assume that these properties are ones that college students should be able to identify at a reasonable degree of accuracy. If they can, this would suggest that the earlier results were primarily due to the failure of spontaneously noticing the property. If they cannot sort the items, this would bring into question how important these properties are in shape and object perception.

Method

Twelve subjects performed four sorting tasks in a within-subjects design; they were asked to sort items on the basis of either symmetry or impossibility. In one task, they were explicitly told that some of the figures were symmetric, with each half being a mirror image of the other, and that others were not, and that they should divide the figures into those two groups. On the other task, they were told that some drawings depicted possible objects that could be constructed in real life, and that the others did not. Again, they were asked to divide the figures into those two groups.

The four stimulus sets consisted of the two unpaired sets of symmetrical–asymmetrical drawings and the two unpaired sets of possible–impossible drawings from the previous experiments. Subjects performed the symmetry task on each of the two sets separately, and then the impossible sorting task on each of the two sets, or vice versa. (Interleaving the sorts seemed likely to cause confusion.) The order of the sorting tasks and the order of testing the two sets of stimuli were counterbalanced across subjects.

Results and discussion

The results are easy to describe. In the symmetry sorts, no subject made errors. However, in the impossible-figure sorts, most subjects made an error of some kind, and a few were poor at the task. All subjects created groups in which the majority of items were possible versus impossible, as instructed, but nine of the 12 subjects made at least one error (see Table 1). Including all subjects, the average number of misplaced cards per sort was low, $M = 1.2$. Among subjects who made errors, the mean number of misplaced cards was 2.2. Two of the subjects found the task difficult, each making a total of seven errors across the two sorts.

Replication Recall that in Experiment 1, we reported a replication of the sorting results with 14 new subjects, of whom only two sorted perfectly. After the other 12 subjects finished sorting, we then explicitly asked them to sort the figures into possible and impossible objects. Replicating the results just reported, we found that a total of six sorted perfectly, and five subjects made one or more errors (two made one error, two made two errors, and one made four errors), with a mean of two misplaced cards among those who made errors. Only one person reported not being able to "see" the impossibility—that is, stating that the figures were "different, complex, and dynamic, but that they could be geometrically sensible with some justification or with some twists." These results are quite similar to those from the main experiment, in that all but one subject could do the task, but errors were common.

These results are interesting in revealing a strong difference between the two global properties: People have no trouble understanding and perceiving symmetry, but they had a range of abilities in identifying possible and impossible figures. Most subjects made no or one error in each sort, but a few subjects made multiple errors, suggesting that they did not readily perceive the difference.

We will discuss how these results shed light on the other sorting results in the General Discussion. However, it is worth pointing out now that an error or two in sorting possible versus impossible figures would not have prevented subjects in Experiments 1–3 from getting credit for using this dimension in their sorting. If they gave an appropriate rationale for their sorting, performance errors were not counted against their using impossibility as a basis for sorting.

General discussion

In the present experiments, we used concept formation as a window into people's spontaneous perception of impossibility and other global properties of objects. This technique has the advantage that it is completely nondirective, unlike more pointed questions about perception, which might draw attention to the property or feature of interest. Furthermore, this technique contains an implicit measure of how salient or important observers find particular features or qualities, since numerous properties could potentially be used to sort objects. Indeed, many subjects preferred to classify items on the basis of curvature or to make pairs of similar items when possible.

The striking overall result was that impossibility was not a dominant property of the stimulus set. Very few subjects grouped the images by this dimension in their first attempt at sorting, which presumably reflects the most obvious perceptual differences among the objects. And, on average, only about half of the subjects used impossibility as a basis for free-form sorting at all. Surprisingly, only when they were given explicit instruction about the nature of the images did observers consistently group them by impossibility. Symmetry was also not a dominant property, also being used by about half of the subjects at some time. In contrast, shape complexity (defined by the number of vertices in a figure) was readily perceived and used for sorting.

Because the amounts of sorting differed across experiments and were inherently somewhat variable, since each sort subject had a binary outcome, we aggregated the data from all of the experiments with possible and impossible figures (Exps. 1 and 3, all conditions, plus the replication) to derive a more stable estimate of effect size. We were particularly interested in the question of just how salient impossibility is, so we looked in particular at the initial sorts (which also avoided issues related to differing numbers of sorting attempts across experiments). That is, if the presence of half possible and half impossible objects was a salient property to subjects, we would expect people to use it as a basis for sorting over more arbitrary visual differences, such as curved–straight and so forth. Among the 62 subjects in those experiments, only 13, or 21 %, sorted on impossibility in their initial sorts. The 95 % confidence interval for this percentage was 11 %–31 %. Therefore, it seems safe to say that under a third of our population spontaneously perceived the possible–impossible difference and found it salient.

Interestingly, a similar pattern of behavior was obtained when young children were observed in sorting tasks using these stimuli (Shuwairi, Tran, Belardo, & Murphy, 2014). They tended to match in pairs or to make small groups based on a single perceptual property (e.g., all of the round ones, or the things with lots of pointy sides). Sorting on the basis of a single feature or property is acquired in early development and reinforced in the North American education system (Sharp, Cole, & Lave, 1979), and it continues to dominate in adult thinking, as well (Medin et al., 1987). However, impossibility is apparently not a very salient dimension on which to classify drawings.

We have suggested that the difference between the properties that were often versus seldom used for sorting has to do with global versus local pictorial properties. Given that no content differences were available on which to sort the items (see below), subjects had to rely on shape and other perceptual properties to divide up the pictures. Although complexity could be defined as a global variable, it in fact altered local sections of each figure, as well. That is, in any given segment of a figure, the complex version had more vertices and was more jagged than its corresponding simple version. In contrast, detecting impossibility and symmetry requires encoding more global properties of the figure, and interpreting impossibility furthermore requires the integration of local depth information, as well as discerning the spatial relations among several portions of the figure to construct a 3-D representation.

One possible explanation of our findings is that people could not identify the critical properties in the stimuli. This is clearly not true for the symmetric figures, since Experiment 4 showed that every subject perfectly divided the shapes into symmetric and asymmetric groups when instructed to do so. The results for impossibility were more mixed. The task was clearly harder, and many people made one or two errors. However, even the two worst subjects made only three and four errors (of 12 figures), suggesting that they could correctly perceive two-thirds of the figures.

It is important to emphasize that our coding did not require perfection in sorting, but instead focused on subjects' stated rationales for separation (though perfectly sorting figures on a tested dimension was also coded as use of that dimension). So, if someone like the two poor performers in Experiment 4 had divided up items into "normal objects" and "weird ones that have something wrong with them," they would be given credit for using impossibility as a sorting basis, even if they placed some figures into the wrong category. Even subjects whose 3-D interpretations of these drawings were not very good could surely have seen that *some* of the figures were impossible, which would then seem to be a strong basis for grouping. Yet, many subjects failed to do this, especially in their first sorts.

Our findings are consistent with earlier computational studies (Cowan & Pringle, 1978; Cowie & Perrott, 1993; Donnelly, Found, & Müller, 1999) that found that the global property of impossibility is not processed initially—that is, in early preattentive vision. It may be that interpreting impossibility requires one to selectively attend in a serial manner to local contour geometry and to the spatial relations among parts, a task that not every observer will do.

Our results may appear to diverge from the research using impossible figures in memory and priming tasks. That work has suggested that the failure to form a coherent interpretation of an impossible figure led to immediate cognitive effects on its representation. Even if those effects were due to other correlated variables (e.g., complexity), such results may seem to contradict our finding that many of the subjects in our study *never* separated possible from impossible figures, even with multiple opportunities.

The implicit memory effect described by Cooper, Schacter, and colleagues (Cooper & Schacter, 1992; Schacter et al., 1990, 1991) did not initially ask observers to identify the nature of the drawing, but used an incidental-learning task (as a familiarization phase) in which subjects determined whether each figure was facing left or right. Any effect of impossibility on the initial encoding of the figure would be demonstrated by its later consequences on the speed and accuracy of structural possibility judgments in the test phase. Also, Cooper and colleagues' studies focused on the nature of stored mental representations of structurally coherent versus incoherent shape configurations, whereas we were evaluating the nature of conceptual knowledge about such objects. In our task, people had to explicitly identify impossibility (or something like it) as a property, and then classify each item on that basis. So, it may well be that our subjects *were* affected by a figure's impossibility in terms of their perceptual or memory representations, but not in explicitly identifying the figure as a member of the category of objects that are either possible or impossible. Since category construction involves making a conscious, verbalizable decision, any implicit effects on perception might not affect it.

Similarly, symmetry influences perception implicitly, as when it makes people more likely to perceive a shape in noise (Machilsen et al., 2009). In such a task, the perception of symmetry is not queried—it is an independent variable. Similarly, the use of symmetry as a Gestalt cue does not involve people explicitly stating that a figure is symmetric, but rather using symmetry as a cue to grouping decisions. Biederman (1987) includes symmetry as a nonaccidental property that provides strong information about object shape. However, like other such cues, people do not need to consciously identify and think about it in order for it to influence object perception.

In some sense, our results for symmetry are even more surprising than those for object possibility, because people were so good at dividing up the figures on the basis of symmetry when instructed to do so (no errors at all). Unlike impossibility, symmetry is a property that is present in nature and discussed in everyday life (e.g., with art, architecture, design, body morphology, physiology, mathematics, etc.). Therefore, it is puzzling that some observers never seemed to notice that half of the figures were symmetrical and half asymmetrical, and therefore never used that as a basis for sorting.

Solving the impossible puzzle

Identifying a drawing as impossible requires the observer to explicitly note the relationship between the drawing's parts and to realize that they do not resolve into a simple 3-D relationship. It is a *formal* property, but observers typically are interested in identifying the *content* of a depiction. Laypeople often seem surprisingly insensitive to the formal properties of depictions. Photography instruction books spend considerable time teaching amateur photographers not to commit obvious errors, such as leaving the subject as a tiny part of the image, making strangely unbalanced compositions, or creating unfortunate conjunctions such as the proverbial lamp seeming to grow out of a person's head. Even after taking and printing the photo, another observer may have to point out that the lamp has apparently become a cranial growth before the proud photographer notices it. The photographer wanted a picture of Uncle Paul, and the picture *is* a photo of Uncle Paul. That content may dominate perception of the composition.

An Escher print is interesting because of the spatial contradiction between the different parts (e.g., water in a circuit continually flowing downhill), while at the same time depicting locally coherent content such as animals, architectural details, and figures. At first viewing, the content is interpreted, and the structural inconsistency of the print may not be immediately apparent. Indeed, the authors have heard anecdotes of people who worked or lived for months in the presence of an Escher print and did not realize that there was anything unusual about it until someone pointed it out to them.

Attention to content over form is apparent in other domains, as well. Journal editors are often surprised to find that even experienced authors, who have read (or written) dozens of published articles still have no idea what proper heading style is or what a table of results should look like. Authors may put the name of their new theory in italics, underlined, and in quotation marks simultaneously, even though they have never seen a published document with such enthusiastic typography. When reading, their attention was focused on the name, and the typographical conventions were never encoded.

O'Regan and Noë (2001) proposed that the awareness of visual properties depends on action on the environment, from eye movements and bodily motion to directly manipulating an object. Knowledge of the visual world consists of knowing how visual stimulation would change if one were to move or blink (etc.), or if the light were to dim or change direction (etc.). Action, either real or prospective, is therefore an important basis for the awareness of visual properties. One possible consequence of this viewpoint (as was pointed out by a reviewer) is that people with expertise in looking for certain local elements as well as in interpreting the global aspects of images or displays presented to them (e.g., visual artists, proofreaders, radiologists) may see these properties much more readily than people who have not had such training. This may well also be true for interpreting 2-D images as 3-D objects, as is required in distinguishing possible from impossible objects. Thus, this perspective may provide a way of thinking about individual differences in who does and who does not spontaneously notice such properties.

However, this approach may not help as much in understanding just why some dimensions jump out and others are less salient. For example, why is impossibility not immediately noticed and used, whereas complexity is? It is not at all clear that the complexity of a nonsensical 2-D shape is something that people have much practice in perceiving. To explain why some dimensions require special practice and others do not, we may have to rely on variables such as computational complexity.

Our study cannot reveal why some people seem sensitive to formal properties of this sort whereas others do not notice them. What is striking is that figural impossibility seems to be one of those formal properties that is often not readily noticed by untrained laypeople, even if it affects the perceptual and memory representations that people form. Additional research will be needed to evaluate the nature and development of our conceptual understanding of the local pictorial input and global geometric properties—such as symmetry, complexity, and possibility—that characterize depicted 3-D objects.

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References

Ahn, W.-K., & Medin, D. L. (1992). A two-stage model of category construction. *Cognitive Science, 16,* 81–121. doi:10.1207/s15516709cog1601_3

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review, 94,* 115–147. doi:10.1037/0033-295X.94.2.115

Biederman, I., & Ju, G. (1988). Surface versus edge-based determinants of visual recognition. *Cognitive Psychology, 20,* 38–64.

Carrasco, M., & Seamon, J. G. (1996). Priming impossible figures in the object decision test: The critical importance of perceived stimulus complexity. *Psychonomic Bulletin & Review, 3,* 344–351. doi:10.3758/BF03210758

Cooper, L. A., & Schacter, D. L. (1992). Dissociation between structural and episodic representations of visual objects. *Current Directions in Psychological Science, 1,* 141–145.

Cowan, T. M., & Pringle, R. (1978). An investigation of the cues responsible for figure impossibility. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 112–120. doi:10.1037/0096-1523.4.1.112

Cowie, R., & Perrott, R. (1993). From line drawings to impressions of 3D objects: Developing a model to account for the shapes that people see. *Image and Vision Computing, 11,* 342–352.

Donnelly, N., Found, A., & Müller, H. J. (1999). Searching for impossible objects: Processing form and attributes in early vision. *Perception & Psychophysics, 61,* 675–690.

Enns, J. T. (1992). Sensitivity of early human vision to 3-D orientation in line drawings. *Canadian Journal of Psychology, 46,* 143–169. doi:10.1037/h0084318

Enns, J. T., & Rensink, R. A. (1991). Preattentive recovery of three-dimensional orientation from line drawings. *Psychological Review, 98,* 335–351. doi:10.1037/0033-295X.98.3.335

Hull, C. L. (1920). Quantitative aspects of evolution of concepts: An experimental study. *Psychological Monographs, 28*(1), 1–86. doi:10.1037/h0093130

Lassaline, M. E., & Murphy, G. L. (1996). Induction and category coherence. *Psychonomic Bulletin & Review, 3,* 95–99. doi:10.3758/BF03210747

Liu, T., & Cooper, L. A. (2001). The influence of task requirements on priming in object decision and matching. *Memory & Cognition, 29,* 874–882. doi:10.3758/BF03196416

Machilsen, B., Pauwels, M., & Wagemans, J. (2009). The role of vertical mirror symmetry in visual shape detection. *Journal of Vision, 9*(12), 1–11. doi:10.1167/9.12.11.

Markman, A. B., & Gentner, D. (1993). Structural alignment during similarity comparisons. *Cognitive Psychology, 25,* 431–467.

Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society B, 200,* 269–294.

Medin, D. L., Wattenmaker, W. D., & Hampson, S. E. (1987). Family resemblance, conceptual cohesiveness, and category construction. *Cognitive Psychology, 19,* 242–279.

Murphy, G. L. (2002). *The big book of concepts*. Cambridge, MA: MIT Press.

O'Regan, J. K., & Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences, 24,* 939–973. doi:10.1017/S0140525X01000115. disc. 973–1031.

Palmer, S. E., & Hemenway, K. (1978). Orientation and symmetry: Effects of multiple, rotational, and near symmetries. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 691–702. doi:10.1037/0096-1523.4.4.691

Ratcliff, R., & McKoon, G. (1995). Bias in the priming of object decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 754–767. doi:10.1037/0278-7393.21.3.754

Regehr, G., & Brooks, L. R. (1995). Category organization in free classification: The organizing effect of an array of stimuli. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 347–363. doi:10.1037/0278-7393.21.2.347

Rock, I., & Leamon, R. (1963). An experimental analysis of visual symmetry. *Acta Psychologica, 21,* 171–183.

Rosch, E. (1973). Natural categories. *Cognitive Psychology, 4,* 328–350.

Rosch, E., & Mervis, C. B. (1975). Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology, 7,* 573–605. doi:10.1016/0010-0285(75)90024-9

Schacter, D. L., Cooper, L. A., & Delaney, S. M. (1990). Implicit memory for unfamiliar objects depends on access to structural descriptions. *Journal of Experimental Psychology: General, 119,* 5–24. doi:10.1037/0096-3445.119.1.5

Schacter, D. L., Cooper, L. A., Delaney, S. M., Peterson, M. A., & Tharan, M. (1991). Implicit memory for possible and impossible objects: Constraints on the construction of structural descriptions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 3–19. doi:10.1037/0278-7393.17.1.3

Sharp, D., Cole, M., & Lave, C. (1979). Education and cognitive development: The evidence from experimental research. *Monographs of the Society for Research in Child Development*, *44*(Serial No. 148, Nos. 1–2).

Shuwairi, S. M. (2009). Preference for impossible figures in 4-month-old infants. *Journal of Experimental Child Psychology, 104,* 115–123.

Shuwairi, S. M., Albert, M. K., & Johnson, S. P. (2007). Discrimination of possible and impossible objects in infancy. *Psychological Science, 18,* 303–307. doi:10.1111/j.1467-9280.2007.01893.x

Shuwairi, S., & Johnson, S. (2013a). Differential oculomotor activity in young infants viewing pictures of possible and impossible objects [Abstract]. *Journal of Vision, 13*(9), 734a. doi:10.1167/13.9.734

Shuwairi, S. M., & Johnson, S. P. (2013b). Oculomotor exploration of impossible figures in early infancy. *Infancy, 18,* 221–232.

Shuwairi, S. M., Tran, A., Belardo, J., & Murphy, G. (2014). *Conceptual understanding of structure and function in children: categorization of complex, asymmetric and impossible figures*. Manuscript in preparation.

Shuwairi, S. M., Tran, A., DeLoache, J. S., & Johnson, S. P. (2010). Infants' response to pictures of impossible objects. *Infancy, 15,* 636–649.

Soldan, A., Hilton, H. J., Cooper, L. A., & Stern, Y. (2009). Priming of familiar and unfamiliar visual objects over delays in young and older adults. *Psychology and Aging, 24,* 93–104.

Spalding, T. L., & Murphy, G. L. (1996). Effects of background knowledge on category construction. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 525–538. doi:10.1037/0278-7393.22.2.525

Sugihara, K. (1982). Classification of impossible objects. *Perception, 11,* 65–74.

Sugihara, K. (2008). Computer-aided creation of impossible objects and impossible motions. In H. Ito, M. Kano, N. Katoh, & Y. Uno (Eds.), *Computational geometry and graph theory* (Vol. 4535, pp. 201–212). Berlin, Germany: Springer.

Wertheimer, M. (1958). Principles of perceptual organization. In D. C. Beardslee & M. Wertheimer (Eds.), *Readings in perception* (pp. 115–135). Oxford, UK: Van Nostrand.

Wolfe, J. M., & Friedman-Hill, S. R. (1992). On the role of symmetry in visual search. *Psychological Science, 3,* 194–198. doi:10.1111/j.1467-9280.1992.tb00026.x

Zaidi, Q. (2005). A sculpture technique for rendering complex impossible objects. *Perception, 34,* 121–123. doi:10.1068/p5359