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Traditional and new principles of perceptual grouping

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Abstract

Perceptual grouping refers to the process of determining which regions and parts of the visual scene belong together as parts of higher order perceptual units such as objects or patterns. In the early 20th century, Gestalt psychologists identified a set of classic grouping principles which specified how some image features lead to grouping between elements given that all other factors were held constant. Modern vision scientists have expanded this list to cover a wide range of image features but have also expanded the importance of learning and other non-image factors. Unlike early Gestalt accounts which were based largely on visual demonstrations, modern theories are often explicitly quantitative and involve detailed models of how various image features modulate grouping. Work has also been done to understand the rules by which different grouping principles integrate to form a final percept. This chapter gives an overview of the classic principles, modern developments in understanding them, and new principles and the evidence for them. There is also discussion of some of the larger theoretical issues about grouping such as at what stage of visual processing it occurs and what types of neural mechanisms may implement grouping principles.

Keywords: perceptual grouping; Gestalt; segregation; perception; perceptual hierarchy; image-based; top-down; vision; perceptual organization

Within the wider study of perceptual organization, research on *perceptual grouping* examines how our visual system determines what regions of an image belong together as objects (or other useful perceptual units). This is necessary because many objects in real world scenes do not project to a continuous region of uniform colour, texture and lightness on the retina. Instead, due to occlusion, variations in lighting conditions and surface features, and other factors, different parts of a single object often result in a mosaic of non-contiguous regions with varying characteristics and intervening regions associated with other, overlapping objects. These diverse and disparate image regions must be united (and segregated from those arising from other objects and surfaces) to form meaningful objects which one can recognize and direct actions toward. Also, meaning may appear not only in the shape of individual objects but in the spatial and temporal relationships between them. For instance, the arrangement of individual objects may form a higher-order structure which carries an important meaning such as pebbles on a beach arranged to form a word. Perceptual grouping is one process by which disparate parts of an image can be brought together into higher-order structures and objects.

1. Classic principles of perceptual grouping

Because perceptual grouping is not indicated directly by the pattern of light falling on the retinae, it must be derived from the available sensory information. Work by Gestalt psychologists on this problem in the early twentieth century identified a set of what are now known as *principles* (or factors) of perceptual grouping. Many of the classic principles were first articulated as a set of “laws” by Max Wertheimer (1923). Each classic principle described how grouping amongst a set of elements in a simple image (e.g., Figure 1A) was affected by varying properties of those elements relative to one another. For instance, when the spatial positions of dots are altered such that pairs of dots are more proximal to each other than they are to other dots (Figure 1B), the entire array tends to be seen as four groups of two dots rather than as eight independent dots[1]. Wertheimer called this effect the principle of *proximity* and gave clear demonstrations of its effects on visual perception. Proximity is not the only factor that Wertheimer proposed as a grouping principle. His paper listed what are now considered to be some of the other classic Gestalt principles of perceptual grouping. In this section, I will examine each of these classic principles and describe their origin in Wertheimer’s work as well as review some modern work that has extended our understanding of how these principles work.

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[1] Although grouping is often described as the unification of independent perceptual elements, it is also possible to see this as the segmentation of a larger perceptual unit (the linear group of eight dots) into four smaller groups. Regardless of whether it is segmentation or unification, the end result is the same.

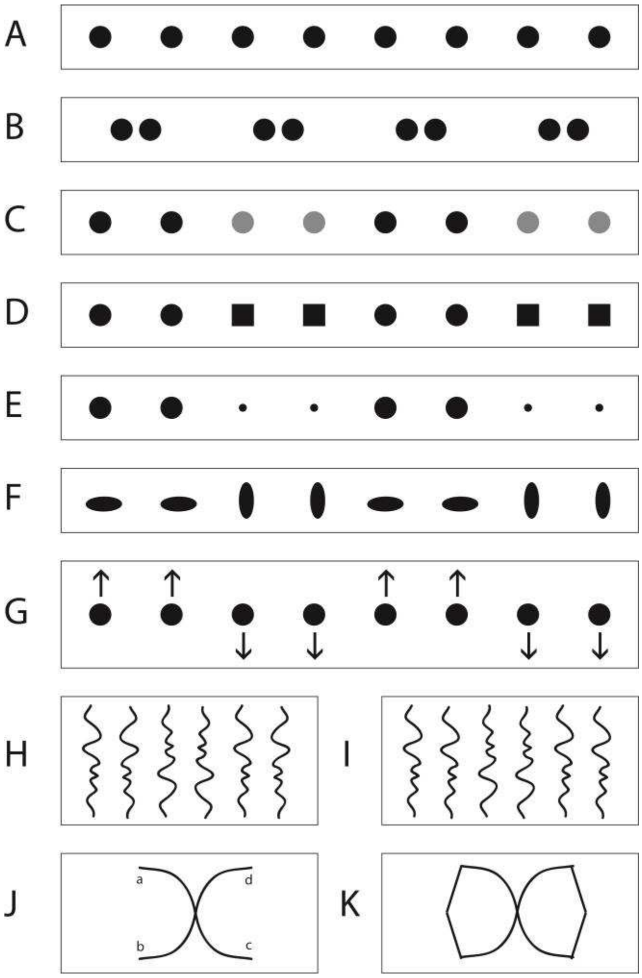

Figure 1. Examples of some classic Gestalt image-based grouping principles between elements. (A) Horizontal array of circular elements with no grouping principles forms a simple line. (B) When the spatial positions of elements are changed, the elements separate into groups on the basis of proximity. Elements can also be grouped by their similarity in various dimensions such as (C) colour, (D) shape, (E) size, and (F) orientation. (G) Similarity in the direction of motion (as indicated by the arrow above or below each element) of elements is referred to as common fate and causes elements with common motion direction to group together. (H) Curvilinear elements can be grouped by symmetry or (I) parallelism. (J) Good continuation also plays a role in determining what parts of a curve go together to form the larger shape. In this case, the edges grouping based on their continuous link from upper left to lower right and lower left to upper right. (K) However, closure can reverse the organisation that is suggested by good continuation and cause perception of a bow-tie shape. Adapted from Palmer (1999) Figure 6.1.2, page 258.

1.1. Proximity – quantitative accounts

Although Wertheimer convincingly demonstrated a role for proximity in grouping, he did not provide a quantitative account of its influence. Early work on this issue by Oyama (1961) used simple, rectangular 4x4 dot lattices in which the distance along one dimension was constant but varied (across trials) along the other dimension (Figure 2A-B). During a 120 second observation period, participants continuously reported (by holding down one of two buttons) whether they saw the lattice as rows or columns at any given time. The results clearly demonstrated that as the distance in one dimension changed (e.g., horizontal dimension in Figure 2A-B) relative to the other dimension, proximity grouping quickly favoured the shortest dimension according to a power function, a relationship found elsewhere in psychophysics (Luce, 2002; Stevens, 1957) and other natural laws. Essentially, when inter-dot distances along one dimension are similar to one another, a small change in inter-dot distance along one dimension can strongly shift perceived grouping. However, the effect of that same change in inter-dot distance falls off as the initial difference in inter-dot distance along the two dimensions grows larger.

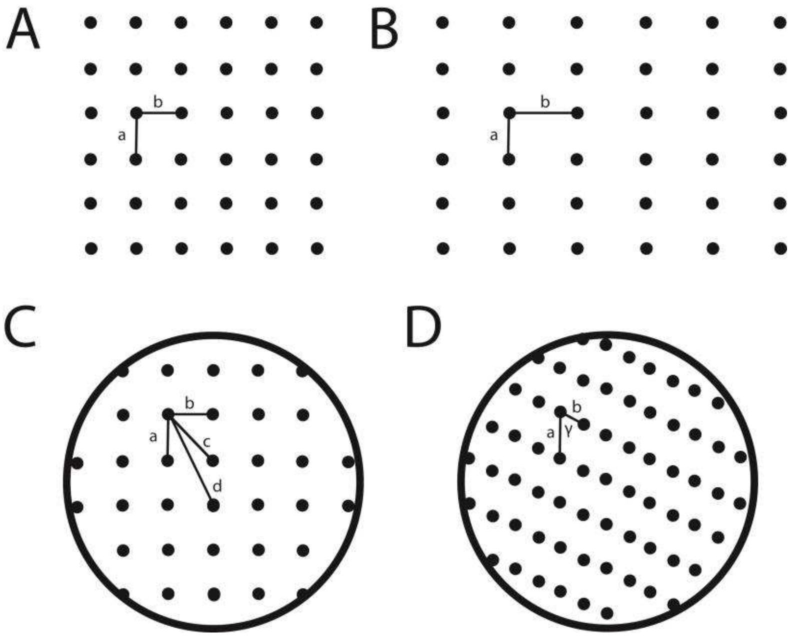

Figure 2. Dot lattices have been used extensively to study the quantitative laws governing grouping by proximity. (A) When distances between dots along vectors a and b are the same, participants are equally likely to see columns and rows. (B) As one distance, *b*, changes relative to the other, *a*, the strength of grouping along the shorter distance is predicted by a negative power function. (C) Dot lattices have many potential vectors, *a-d*, along which grouping could be perceived even in a simple square lattice. (D) Dot lattices can also fall into other classes defined by the relative length of their two shortest inter-dot distances and the angle between these vectors, γ. In all of these lattices, the pure distance law determines the strength of grouping.

The above relationship, however, only captures the relative contributions of two (vectors a and b, Figure 2C) of the many possible organisations (e.g., vectors a-d, Figure 2C) within the lattice. Furthermore, the square and rectangular lattices in Figures 2A-D are only a subset of the space of all possible 2D lattices and the power law relationship may not generalise beyond these cases. In a set of elegant studies, Kubovy and Wagemans (1995) and Kubovy, Holcombe, and Wagemans (1998) first generated a set of stimuli than spanned a large space of dot lattices by varying two basic features: (1) the lengths of their shortest inter-dot distances (vectors a and b, Figure 2C-D) and (2) the angle between these vectors, γ. They then briefly presented these stimuli to participants and asked them to choose which of four orientations matched that of the lattice. They found that across the entire range of lattices in all orientations, grouping depended only on the relative distance between dots in the various possible orientations, a relationship that they called the *pure distance law*. Although the space of all lattices could be categorised into six different classes depending on their symmetry properties, this global configuration aspect did not affect the grouping in these lattices, leaving distance as the only factor that affects proximity grouping. More recently though, it has been found that other factors, such as curvilinear structure, can also play a role in grouping by proximity (Strother & Kubovy, 2006).

1.2. Common fate

Wertheimer appreciated the influence of dynamic properties on grouping when he proposed the well-known principle of *common fate* (Figure 1G). The common fate principle (which Wertheimer also called “uniform destiny”) is the tendency of items that move together to be grouped. Common fate is usually described with grouped elements having exactly parallel motion vectors of equal magnitude as in Figure 1G. However, other correlated patterns of motion such as dots converging on a common point and co-circular motion can also cause grouping (Ahlström, 1995; Börjesson & Ahlström, 1993). Some of these alternative versions of common motion are seen as rigid transformations in three-dimensional space. Although common fate grouping is often considered to be very strong, to my knowledge, there are no quantitative comparisons of its strength with other grouping principles. Recently, it has been proposed that common fate grouping may be explained mechanistically as attentional selection of a direction of motion (Levinthal & Franconeri, 2011).

1.3. Similarity grouping

When two elements in the visual field share common properties, there is a chance that these two elements are parts of the same object or otherwise belong together. This notion forms the basis for the Gestalt grouping principle of *similarity*. One version of similarity grouping, and the one that Wertheimer originally described, involves varying the colours of the elements (Figure 1C). Items that have similar colours appear to group together. However, other features can also be varied such as the shape (Figure 1D), size (Figure 1E), or orientation (Figure 1F) of the elements. Although these variations on the principle of similarity are sometimes demonstrated separately from one another (e.g., Palmer, 1999), Wertheimer appeared to favour the notion of a general principle of similarity when he described it as “the tendency of like parts to band together”. Thus, the list of features given above is not meant to be an exhaustive set of features on which similarity grouping can occur. Instead, there may be as many variations of the similarity principle as there are features to be varied (e.g., texture, specularity, blur). However, many of these variations of similarity grouping have not been studied systematically, if at all. Furthermore, the generality of the similarity principle may also encompass other known principles as variations of similarity. For instance, the principle of proximity may be thought of as similarity of position and classic common fate as similarity of the direction of movement. However, despite the ability to unify these principles logically, the extent to which they share underlying mechanisms is unclear.

1.4. Symmetry

The world does not solely comprise dots aligned in rows or columns. Instead, elements take many forms and can be arranged in patterns with varying forms of regularity. Mirror symmetry is a particular type of regularly that is present in a pattern when half of the pattern is the mirror image of the other half. Such symmetrical patterns have been found to be particularly visually salient. For instance, symmetry has clear effects on detection of patterns in random dot fields, contours, and other stimuli (e.g., Machilsen, Pauwels, & Wagemans, 2009; Norcia, Candy, Pettet, Vildavski, & Tyler, 2002; Wagemans, 1995). However, when a symmetrical pattern is tilted relative to the frontal plane, its features in the image projected to the retinae are no longer symmetrical. Nonetheless, the detection advantage seems to be robust even in these cases of skewed symmetry although it is clearest if symmetry is present in several axes (e.g., Wagemans, Van Gool, & d’Ydewalle, 1991; Wagemans, 1993). However, not all symmetries are equal. A substantial number of studies have found that symmetry along a vertical axis is more advantageous than symmetry along other axes (e.g., Kahn & Foster, 1986; Palmer & Hemenway, 1978; Royer, 1981). However, symmetry along the horizontal axis has also been found to be stronger than symmetry along oblique angles (e.g., Fisher & Bornstein, 1982). Symmetry detection is also robust to small deviations in the corresponding positions of elements in the two halves of the symmetric pattern (Barlow & Reeves, 1979). The study of symmetry, its effects on detection and factors that modulate it has been extensive and this is discussed in more detail elsewhere in this volume (van der Helm, "Symmetry Perception" chapter, this volume). It is important to point out that many studies of symmetry (including those mentioned above) do not measure perceived grouping directly as was often the case for many of the other principles described above. Symmetry grouping has tended to be measured by its effect on pattern detection or ability to find a pattern in noise. The extent to which performance in these tasks reflects perceived grouping, per se, rather than other task-related changes due to symmetry is unclear. Nonetheless, demonstrations of symmetry grouping are often presented as evidence of the effect (e.g., Figure 1H).

One rationale for a symmetry grouping and detection mechanisms is that is designed to highlight non-accidental properties that are unlikely to have been caused by chance alignment of independent elements. Alternatively, symmetry may allow particularly efficient mental or neural representations of patterns (van der Helm, "Simplicity in Perceptual Organization" chapter, this volume). Symmetry also appears to be a common feature of the visual environment. Artefacts of many organisms are often symmetrical (Shubnikov & Koptsik, 1974; Weyl, 1952). However, it is not clear whether this is a cause of visual sensitivity to symmetry, an effect of it, or whether both of these are caused by some other adaptive benefit of symmetry.

1.5. Good continuation, relatability, closure, and parallelism

The principle of *good continuation* is often demonstrated by showing that some line segments form a “better” continuation of a particular curve. For instance, the line segments in Figure 1J are likely to be seen as two, continuous intersecting curves, one going from upper left to lower right (segments *a* + *c*) and the other from lower left to upper right (segments *b* + *d*). Of course, one could see a+b and d+c or even a+d and b+c but these are seen as less good continuations and thus less likely to be perceived. What defines a good continuation? Wertheimer (1923) suggested that good continuations of a segment proceed in a direction that “carry on the principle logically demanded” from the original element, i.e. a “factor of direction”[2], as he actually called it. In Figure 1J this seems to correspond roughly to collinearity, or minimal change in direction, because at their junction ac and bd are more collinear than the alternative arrangements. However, other examples that he used (Figure 3B) suggest that this may not be exactly what he meant. Wertheimer’s definition was not specific and largely based on intuition and a few demonstrations.

In modern work, good continuation has been largely linked with work on contour integration and visual interpolation. Contour integration studies largely examine what factors promote grouping of separate (not connected) oriented elements (Figure 3C) into contours which are detectable in a field of otherwise randomly oriented elements. Collinearity, co-circularity, smoothness, and a few other features play prominent roles in models of good continuation effects on contour integration (e.g., Fantoni & Gerbino, 2003; Field, Hayes, & Hess, 1993; Geisler, Perry, Super, & Gallogly, 2001; Hess, May, & Dumoulin, this volume; Pizlo, Salach-Golyska, & Rosenfeld, 1997; Yen & Finkel, 1998).

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[2] Wertheimer also used the term “factor of good curve” in this section of his manuscript to describe an effect that seems to be similar to his use of “factor of direction” and the modern use of good continuation. However, Wertheimer did not explicitly describe any differences between the nature of these two factors.

Although these definitions of good continuation are clearly specified, the stimuli and tasks used are very different from those of Wertheimer and may have different mechanisms.

Good continuation is also often invoked in models of interpolation which determine the likelihood of filling in a contour between two segments on either side of an occluder (e.g., Wouterlood & Boselie, 1992). One criterion for interpolation is whether two contours are *relatable* (Kellman & Shipley, 1991), i.e. whether a smooth monotonic curve could connect them (roughly speaking). Relatability is another possible formal definition of good continuation although they may be related but distinct concepts (Kellman, Garrigan, Kalar, & Shipley, 2010). This is an issue that needs further study. Completion and its mechanisms is discussed at length elsewhere in this volume (Singh; van Lier & Gerbino).

Wertheimer also recognized the role for closure in grouping of contours. This is demonstrated in the bow-tie shape in Figure 1K which overcomes the grouping by good continuation that was stronger in Figure 1J. Several contour integration studies have also examined the role of *closure* in perceptual grouping of contour elements. Many find effects of closure on grouping and contour detection (e.g., Mathes & Fahle, 2007) although these may be explainable by other mechanisms (Tversky, Geisler, & Perry, 2004). Contours can also be grouped by parallelism (Figure 1I). However, this effect does not appear to be particularly strong and contour symmetry seems to be better detected (e.g., Baylis & Driver, 1994; Corballis & Roldan, 1974).

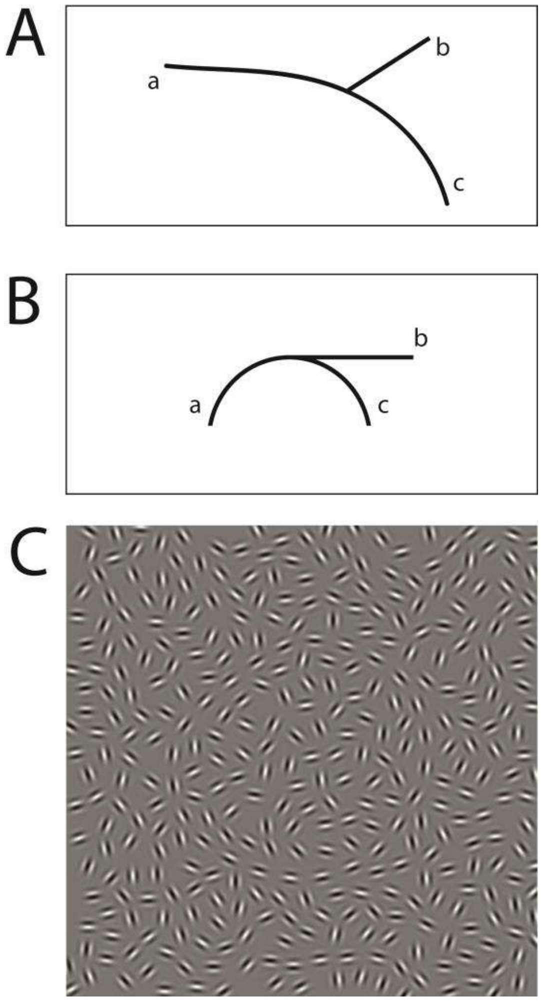

Figure 3. (A) Good continuation favours a grouping of ac with b as an appendage. This may be due to the c being collinear or continuing the same direction as a. (B) Good

continuation may not always favour the smallest change in direction. Segment c seems to be a better completion of a than b despite b being tangent to the curve (and thus having minimum difference in direction) at their point of intersection. (C) A stimulus commonly used in contour integration experiments with a circular target contour created by good continuation and closure in the alignment of the elements.

1.6. *Ceteris paribus rules*

The classic grouping principles described above have stood the test of time and have formed the basis for a substantial amount of modern research on perceptual grouping. Even from the first demonstrations by Wertheimer though, it was clear that the principles are not absolute. Rather, they operate as *ceteris paribus* rules. This Latin phrase is translated literally as “other things being equal”. Thus, as long as other factors are equated between two elements, then the factor in question will affect grouping between the elements. By creating simple displays, which varied one factor at a time, the Gestalt psychologists were able to provide convincing evidence for their principles. In any given display though, multiple factors can be present at once and in this case, factors may reinforce one another or compete against one another. For example, proximity of elements in the array in Figure 4A may favour grouping to form rows. This organization is also supported by the similarity of the colours. However, Figure 4B shows an example of how colour similarity and proximity may work in opposition of one another. In this case, the grouping becomes somewhat ambiguous. Ultimately, the resulting organization depends on the relative strengths of the two grouping factors. With proximity at nearly maximum, it gains the upper hand and can overcome the competing influence of colour similarity (Figure 4C). Pitting grouping principles against one another has served as one way to measure the relative strength of grouping principles (e.g., Hochberg & Silverstein, 1956; Oyama, Simizu, & Tozawa, 1999; Quinlan & Wilton, 1998). However, some grouping principles may operate faster than others and this may affect their relative effectiveness against one another in addition to the relative degree to which each principle is present in the display (Ben-Av & Sagi, 1995).

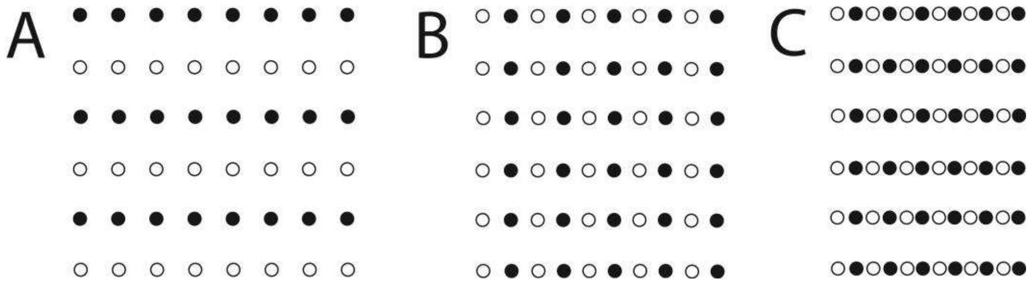

Figure 4. When multiple grouping principles are present in the same display, they may reinforce one another or compete against one another. (A) When both proximity and colour similarity (indicated by filled vs. unfilled dots here) favour organization into rows, they reinforce each other and result in a clear perception of rows. (B) When proximity grouping favours a rows organization and colour similarity favours columns, the factors compete against one another and this can result in perceptual ambiguity. (C) With near maximal proximity of elements favouring rows, this factor can overcome the competition with colour similarity and result in a perception of rows.

2. Recent principles of perceptual grouping

The classic Gestalt grouping principles dominated the stage for most of the 20th century. However, within the last 20-30 years, modern vision scientists have begun to articulate new principles of grouping. Some of these are variations or generalisations of Gestalt principles but others are completely new. Several of these involve dynamic properties of stimuli which are much easier to appreciate given modern computerised methods for generating visual content. Although many of the new principles can be appreciated by demonstrations, modern vision scientists typically quantify their data using measures of phenomenological psychophysics (Strother, Van Valkenburg, & Kubovy, 2002), which quantify the reported perceptual outcomes, as well as indirect measures which reflect effects of grouping on task performance. For some principles, this has led to a robust understanding of the conditions under which they occur and factors that affect their functioning. The sections below attempt to describe most of these recent grouping principles and what we know about their function.

2.1. Common region

The principle of common region (Figure 5B) recognises the tendency for elements that lie within the same bounded region to be grouped together (Palmer, 1992). Elements grouped by common region lie within a single, continuous and homogenously coloured or textured region of space or within the confines of a bounding contour. The ecological rationale for this grouping principle is clear. If two elements, eyes for instance, are contained within an image region, of a head, then they are likely to belong together as part of that object rather than accidentally appearing together within the same region of space. The effects of common region can compete effectively against other grouping principles such as colour similarity (Figure 5C) and proximity (Figure 5D). Palmer (1992) also found evidence that the common region principle operates on a three dimensional representation of the world. When he placed elements within overlapping regions, there was no basis for grouping to go one way or the other. However, if the dot elements were placed in the same depth plane as some of the oval regions, then the dots tended to be grouped according to the regions within their same depth plane. These results suggest that grouping by common region can operate on information that results from computations of depth in images and thus may not be simply an early, low-level visual process. It is also worth noting that unlike all of the classic Gestalt principles which are defined around the relative properties of the elements themselves, grouping by common region depends on a feature of another element (i.e., the bounding edge or enclosing region) separate from the grouped elements themselves. Although common region can be appreciated through demonstrations like those in Figure 5, indirect methods have provided corroborative evidence for this grouping factor and others. For instance, in the *Repetition Discrimination Task,* abbreviated *RDT,* (Palmer & Beck, 2007) participants see a row of elements which alternates between circles and squares. One of the elements, either the circle or the square repeats at one point, and the participant's task is to report which shape it is. Participants are faster at this when the repeat occurs within the same group (Figure 5E) than when it appears between two different groups (Figure 5F). Because performance on this task is modulated by grouping, it can be used to quantify grouping effects indirectly and corroborate findings in direct subjective report tasks. Although such indirect measures may be less susceptible to demand characteristics, it is important to point out that there is no guarantee that they reflect purely what people actually see. Indirect measures may also reflect a history of the processing through which a stimulus has gone even if that history is not reflected in the final percept. Such effects have been demonstrated in experiments on figure-ground organization in which two cues are competing against one another to determine which side of an edge is figural. Even though one particular cue always wins the competition and causes figure to be assigned to its side, the presence of a competing cue suggesting figural assignment to the other side affects response time in both direct report and other task such as same-difference matching (e.g., Brooks & Palmer, 2010; Peterson & Enns, 2005). Even clearer cases of the dissociation between implicit measures and conscious perception have been seen in neurological patients. For instance, patients with blindsight can act toward an object even though they cannot consciously see it (e.g., Goodale, Milner, Jakobson, & Carey, 1991).

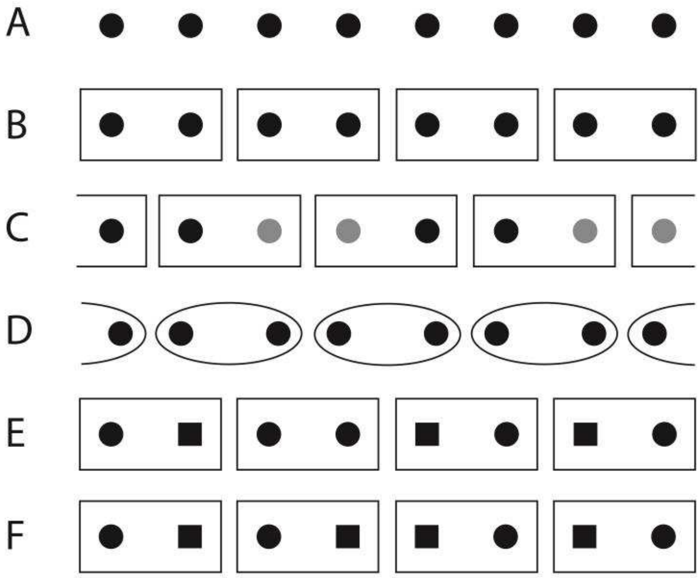

Figure 5. Grouping by common region. (A) A set of ungrouped dots. (B) Dots grouped by common region as indicated by an outline contour. Common region can also be indicated by regions of common colour, texture or other properties. (C) Common region can compete effectively against grouping by colour similarity as well as against (D) grouping by proximity. (E) In the repetition discrimination task, the repetition of two shapes in the element array - two squares here - can occur within the same object or (F) between two different objects.

2.2. Generalized common fate

The classic principle of common fate is typically described as the grouping that results from elements moving with a similar speed and direction. Although Wertheimer described common fate with reference to motion, it is not clear that he intended the definition to be limited to common motion. In a section of text that was not included in the well-known English translation of his work (Wertheimer, 1938), Wertheimer wrote that the common fate principle “applies to a wide range of conditions; how wide, is not discussed here” (Wertheimer, 2012). Recently, Sekuler and Bennett (2001) have demonstrated that grouping can also be mediated by common direction of luminance changes. They presented participants with square grids (Figure 6A) in which the luminance of each square element was initialised at a random value and then modulated sinusoidally over time around its initial luminance. A subset of the elements (outlined in black, Figure 6B) was designated as the target and modulated out of phase with the rest of the elements. Participants had to determine the orientation (horizontal or vertical) of this target. To the extent that elements within the target group together (and segment from the other elements) based on their common luminance changes, discrimination of the target orientation should be easier. The results demonstrated a strong effect of *generalized common fate* by common luminance changes. Importantly, the authors made significant efforts to control for the effects of static luminance cue differences between the target and non-target areas of the image to ensure that this is a truly dynamic cue to grouping. Although this grouping cue has been linked with classic common fate by name, it is not clear whether it is mediated by related mechanisms.

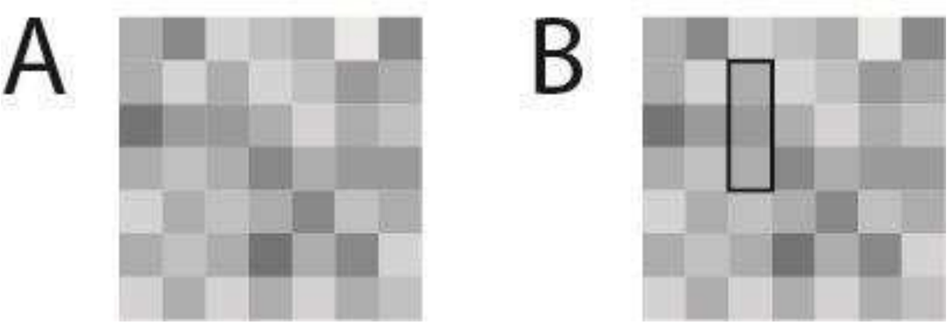

Figure 6. Generalized Common Fate was demonstrated using displays comprising (A) square elements and each element was initially assigned a random luminance and this oscillated over time. (B) For a subset of these elements, the target (outlined in black here), their luminances oscillated out of phase with the rest of the elements. This means that although the elements within the target had varying luminances (and similar to non-target luminances) they were distinguished by their common direction of change.

2.3. Synchrony

The common fate principles discussed above capture how commonalities in the direction of motion or luminance can cause grouping. However, elements which have unrelated directions of change can group on the basis of their temporal simultaneity alone (Alais, Blake, & Lee, 1998; Lee & Blake, 1999). For instance, consider a matrix of small dots which change colour stochastically over time. If a subset of the elements change in synchrony with one another, regardless of their different changes of direction, these elements group together to form a detectable shape within the matrix. Blake and Lee (1999) claimed that in their displays, synchrony grouping cannot be computed on the basis of static information in each frame of the dynamic sequence. This is because, for instance, in the colour change example describe above, the element colours in each frame are identically and randomly distributed within both within the grouped region and the background. It is only the temporal synchrony of the changes that distinguishes the grouped elements from the background. This is in contrast to previous evidence of synchrony grouping which could be computed on the basis of static image differences at any single moment in time (e.g., Leonards, Singer, & Fahle, 1996; Usher & Donnelly, 1998). Lee and Blake argued that purely temporal synchrony requires computing high order statistics of images across time and is a new form of grouping that cannot be explained by known visual mechanisms. However, this claim has proved controversial (Farid & Adelson, 2001; Farid, 2002) and some have argued that temporal structure plays a more important role than temporal synchrony (Guttman, Gilroy, & Blake, 2007). The rationale for the existence of grouping by pure synchrony is also controversial. Although it seems reasonable that synchronous changes in elements of the same object are common in the visual world, it seems unlikely that these are completely uncorrelated in other aspects of the change (as is required for pure synchrony grouping), although this appears not to have been formally tested.

2.4. Element connectedness

Distinct elements that are connected by a third element (Figure 7B) tend to be seen as part of the same group (Palmer & Rock, 1994). This effect can compete effectively against some of the classic grouping principles of proximity and similarity (Figure 7C and 7D) and it doesn’t depend on the connecting element to have the same properties as the elements themselves or to form a continuous unbroken region of homogeneous colour or texture (Figure 7E). The ecological rationale for element connectedness is simple. Many real-world objects comprise several parts that have their own colour, texture, and other properties. Nonetheless, the elements of these objects are often directly connected to one another. The phenomenological demonstration of grouping by element connectedness has also been corroborated by evidence from the RDT (Palmer & Beck, 2007) that was used to provide indirect evidence for the common region principle. The powerful effects of this grouping principle are also evident by how it affects perception of objects by neurological patients. Patients with Balint's syndrome suffer from the symptom of simultanagnosia, i.e., they are unable to perceive more than one object at a time (see Gillebert & Humphreys, this volume). For instance, when presented with two circles on a computer screen, they will likely report only seeing one circle. However, when these two circles are connected by another element to form a barbell shape, the patient can suddenly perceive both of the objects (Humphreys & Riddoch, 1993). Similar effects of element connectedness have been shown to modulate hemi-spatial neglect (Tipper & Behrmann, 1996).

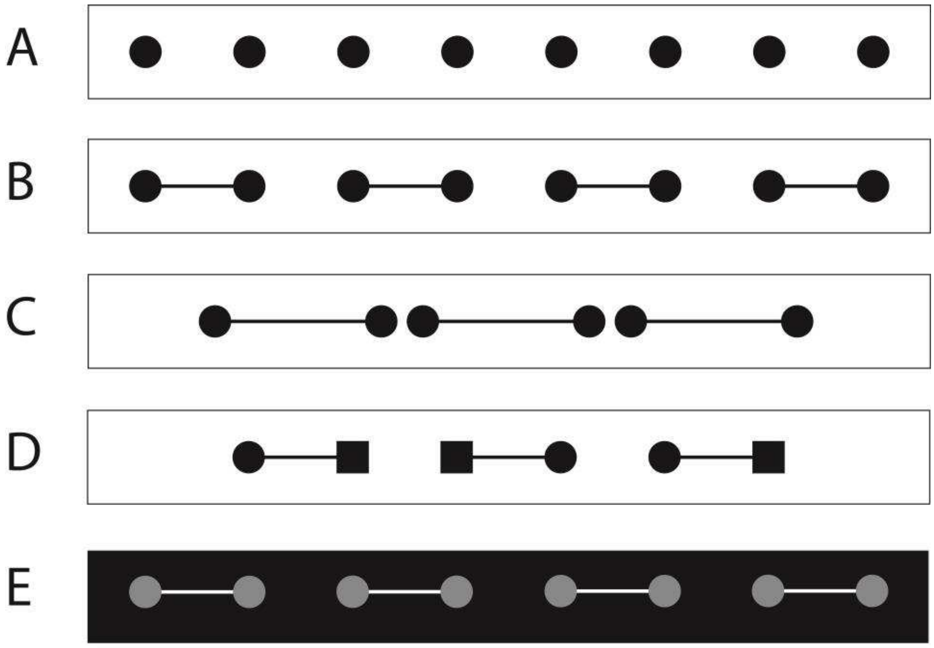

Figure 7. Grouping by element connectedness. (A) Ungrouped elements. (B) Connecting elements into pairs units them into four groups. (C) Element connectedness competes effectively against the classic principle of proximity. (D) Element connectedness competes effectively against the classic principle of similarity. (E) Element connectedness does not require the connecting element to have the same properties or to form a continuous area of the same colour or texture.

2.5. Non-accidentalness and regularity

According to the pure distance law of proximity grouping, the relative distance between elements in two competing organisations is the only driver of grouping strength. This was found to be the case in rectilinear dot lattices (Kubovy & Wagemans, 1995). However, when different dot structures were investigated, it became clear that curvilinear grouping patterns (e.g., Figure 8A) could be stronger than rectilinear groupings (Strother & Kubovy, 2006) even with distance between elements was held constant. This suggests that proximity alone is not the only factor to govern grouping in these patterns. Strother and Kubovy (2012) have suggested that this effect is due to curvilinear arrangements of elements being particularly *non-accidental*. That is, they claim that repeated alignment of elements along parallel curves is very unlikely to have occurred by the chance alignment of independent elements. Therefore, it is more likely that the elements are somehow related to one another and thus should be seen as grouped rather than independent elements. In support of this, Strother and Kubovy found evidence that when two curvilinear grouping patterns were competing against one another (e.g., Figure 8A), the pattern with the stronger curve was more likely to be perceived than the less curved competitor. For instance, the dot stimulus in Figure 8A could be organised along the more shallow curve represented by Figure 8B or along the stronger curve represented by Figure 8C. Greater curvature caused grouping even if the distances between dots along the two curves were equal, ruling out an explanation in terms of proximity. Parallel curvature is one example of non-accidentalness that could be quantified and then systematically varied on the basis of previous work (Feldman, 2001). Other types of feature arrangements can also have this property but a challenge is to quantify and systematically vary non-accidentalness more generally. One possible example of this principle is the tendency to perceive grouping along regular variations in lightness (van den Berg, Kubovy, & Schirillo, 2011). However, it remains unclear whether these two aspects of grouping are mediated by similar mechanisms or fundamentally different ones.

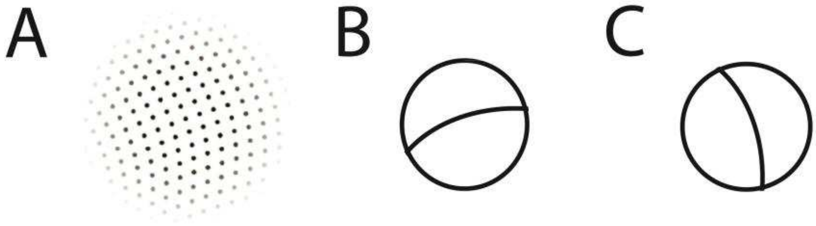

Figure 8. (A) A dot-sampled structured grid with two competing patterns of curvilinear structure. (B) Curvilinear structure along this dimension in panel A has less curvature and is therefore less likely to be perceived in comparison to structure along the direction showed in (C) which has a stronger curve and is most likely to be perceived as the direction of curvilinear grouping.

2.6. Edge-region grouping

Grouping has traditionally involved elements such as dots or lines grouping with other elements of same kind. However, Palmer and Brooks (2008) have proposed that regions of space and their edges can serve as substrates for grouping processes as well and that this can be a powerful determinant of figure-ground organisation. For example, common fate edge-region grouping can be demonstrated in a simple bipartite figure (Figure 9A). This stimulus has two sparsely textured (i.e., the dots) regions of different colours and share the contrast boundary between them. If, for instance, the edge moves in one direction in common fate with the texture of one of the regions but not in common with the other region (Figure 9B; animation in Supplemental Figure S1), then participants will tend to see the region that is in common fate with the edge as figural. It is not necessary for the edge and grouped region to be moving. In fact, if one of the textured regions is moving whereas the edge and the second region are both static, the edge will group with the static region and become figural (Figure 9C; Figure S2). Palmer and Brooks demonstrated that proximity, orientation similarity, blur similarity (Figure 9D-E), synchrony, and colour similarity can all give rise to edge-region grouping, albeit with a range of strengths. Importantly, they also showed that the strength of the induced figure-ground effect correlated strongly with the strength of grouping (between the edge and the region) reported by the participants in a separate grouping task. This suggests a tight coupling between grouping processes and figure-ground processes. However, it is not clear that the grouping mechanisms that mediate edge-region grouping are the same as those that mediate other types of grouping. Nonetheless, edge-region grouping challenges that claim that grouping can only occur after figure-ground organization (Palmer & Rock, 1994).

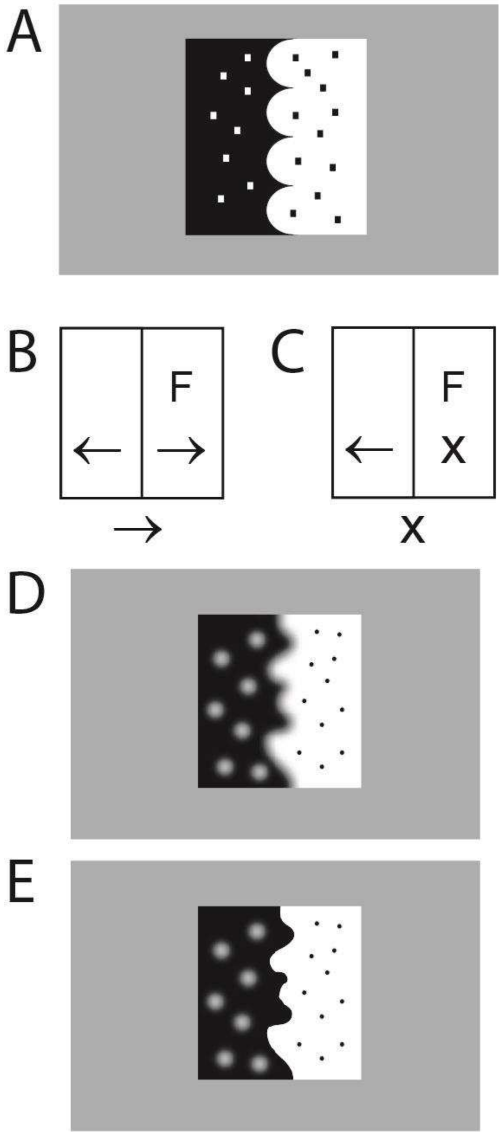

Figure 9. Edge-region grouping occurs between edges and regions. (A) A bipartite display commonly used in figure-ground paradigms contains two adjacent regions of different colour (black and white here) with a contrast edge between them. The regions here are textured with sparse dots. This can be seen as either a black object with sharp spikes in front of a white object or as a white object with soft, rounded bumps in front of a black object. (B) If the texture dots within one region (right region here) move in common fate with the edge (indicated by arrow below the central vertical edge) then that region will tend to group with the edge and be seen as figural. The non-grouped region (left here)

will be seen as background. (C) A region does not need to be moving in order to be grouped. It (right region here; lack of movement indicated by “X”) can be in static common fate with an edge if its texture and the edge are both static while the other region (right region here) is in motion. The region which shares its motion properties with the edge (right here) becomes figural. (D) Edge-region grouping based on blur similarity between the edge and one of the textured regions can cause figural assignment to the left in this case. (E) When the blur of the edge is reduced to match the blur level of the texture elements in the right region then the edge-region grouping causes assignment to the right.

2.7. Induced grouping

The elements in Figure 10A have no basis for grouping amongst themselves. However, when these elements are placed near to other elements which have their own grouping relationships by proximity (Figure 10B), colour similarity (Figure 10C) or element connectedness (Figure 10D), these other groups can cause *induced grouping* in the otherwise ungrouped elements (Vickery, 2008). For instance, element connectedness in the lower row of Figure 10D seems to group the elements of the upper row into pairs. This impression can be seen phenomenologically but it is difficult to determine whether it occurs automatically or because the observer is intentionally looking for it (and thus induced by attention). To solve this problem, Vickery (2008) used the RDT (see Common Region section above) to indirectly measure the effects of grouping and avoid demand characteristics. The results demonstrated clearly that grouping can be induced by similarity, proximity, and common fate. Based on demonstrations, other grouping principles also seem to effectively induce grouping in surrounding elements as well. Induced grouping depends critically on the relationship between the inducing elements (lower rows in Figures 10B-D) and the elements in which grouping is being induced (top rows in Figures 10B-D). For instance, it can be disrupted by using common region to put the inducing set into a separate region of space (Figure 10E).

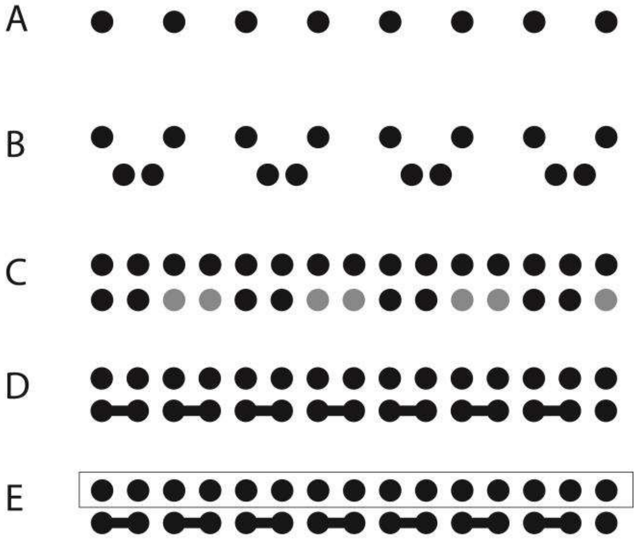

Figure 10. Examples of induced grouping. (A) A set of elements with no adjacent elements to induce grouping. (B) Placing elements grouped by proximity below ungrouped elements can induced grouping within the otherwise ungrouped upper row. (C) Induced grouping by colour similarity. (D) Induced grouping by element connectedness. (E) Induced grouping can be disrupted by segmenting the inducers into a separate group as done here by common region grouping.

2.8. Uniform connectedness

Grouping principles operate on elements such as lines, dots, regions, and edges. How do these elements come about in the first place? One hypothesis has been that these elements are generated by another, early grouping process which partitions an image to form the substrates for the further grouping processes that have been described above (Koffka, 1935; Palmer & Rock, 1994). The principle of *uniform connectedness (UC)* has been proposed to fill this role. UC decomposes an image into continuous regions of uniform image properties, e.g., texture, colour, motion, and depth (e.g., Figure 11A-F). This process is very similar to some computer vision algorithms that have been developed to segment images based on uniform regions of texture and other properties (e.g., Malik & Perona, 1990; Shi & Malik, 2000). The elements created by uniform connectedness were proposed to be *entry-level units* because they were thought of as the starting point for all subsequent grouping and parsing processes. However, this proposal has been controversial. Peterson (1994) has argued that the serial ordering of perceptual organisation suggested by uniform connectedness is not consistent with modern evidence for how these processes operate. Others have found evidence that other principles such as collinearity and closure are as important as uniform connectedness for the initial stages of perceptual organisation (Kimchi, 2000) and that, under some conditions, proximity may operate faster than uniform connectedness (Han, Humphreys, & Chen, 1999; Han & Humphreys, 2003). Although its place in the hierarchy of grouping principles is debated, the basic effect of uniform connectedness as a grouping principle seems to be clear.

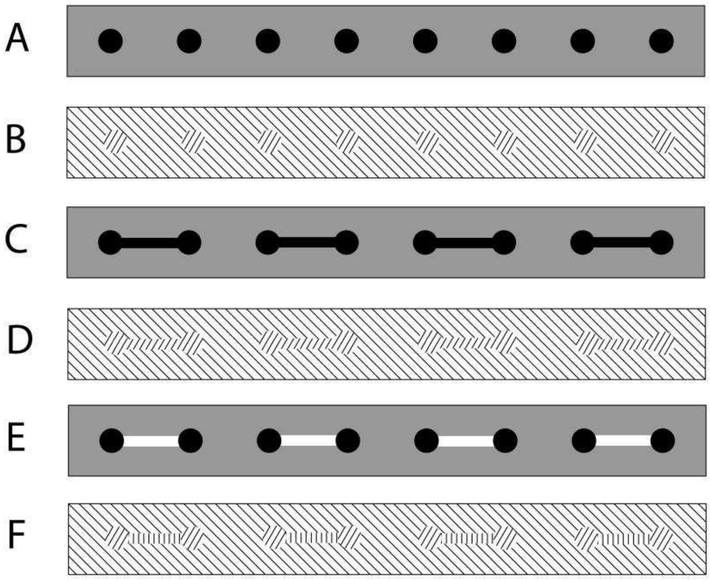

Figure 11. Examples of uniform connectedness adapted from Figure 6.2.1, page 269, Palmer (1999). (A) Each black circle defines its own unique uniformly connected (UC) region and the grey background forms another UC region based on colour. (B) Regions of uniform texture also form UC regions. (C) When two circles are joined by a bar of the same colour or (D) texture, then those two dots join together with the connecting bar to form a single UC region. (E) A bar of different colour or (F) texture from the circles leads to the circles remaining separate UC regions and the bar yet another UC region.

2.9. Grouping in dynamic patterns

Apparent motion arises from displays that are presented in rapid succession with their elements in different spatial locations from one frame to the next (Wertheimer, 1912). With a single element the direction of this perceived motion is usually clear. However, when two elements with similar features are present in the display, the direction of motion can become ambiguous (Figure S3). For instance, if the patterns in Figure 12A and 12B are alternated, one could perceive the dots moving either vertically up and down (Figure 12C) or left and right (Figure 12D). This ambiguity highlights the *correspondence problem*, i.e. how do we know which element in the second frame corresponds to, for instance, the upper left element in the first frame? Notice that this sounds like a grouping problem but operating over time rather than space. Early on, it was clear that varying both the spatial distances between elements and their durations could affect how motion is perceived (e.g., Bruno & Bertamini, this volume; Burt & Sperling, 1981; Herzog & Öğmen, this volume; Hock, this volume; Korte, 1915). For instance, shortening the horizontal distance between the elements in successive frames biases perception toward horizontal motion (Figure S4). However, spatial groupings within each frame may also have an impact. One way to study this systematically has been to use the dot lattice stimuli that have been previously used to study grouping by proximity. Gepshtein and Kubovy (2000) constructed displays with two lattices, $Lattice_{t=1}$ and $Lattice_{t=2}$ which alternated over time (Figure 12E). They found that the perceived direction of apparent motion within these displays depended primarily on two ratios. First, the motion ratio, $r_m = m_1/ m_2$, considers the distances from an element in $Lattice_{t=1}$ to its two closest neighbours in $Lattice_{t=2}$. Similarly to the attraction function for proximity grouping (see section above on proximity grouping), there is a negative linear relationship between the motion ratio and the probability of perceiving motion along m_1. That is, as m_1 distance increases relative to m_2 the likelihood of seeing motion along m_1 decreases. In the case of motion lattices this pattern has been called an *affinity* function. The second ratio, $r_b = b/ m_2$, captures the spatial grouping factors because it takes into consideration the relative distance between elements within each single frame. If the distance b is large (relative to the motion grouping directions) then spatial grouping by proximity (along the dashed line in Figure 12E) is weak and motion grouping can dominate and cause motion along either direction m_1 or m_2. However, when b is relatively small, then spatial grouping by proximity is strong in each frame and it can affect perception of motion. Specifically, it can cause motion along a direction orthogonal to the grouped line of dots (i.e. orthogonal to the dashed line, Figure 12E), a totally different direction than either m_1 or m_2. By manipulating both spatial and motion/temporal grouping parametrically within these displays, Gepshtein and Kubovy (2000) found clear evidence that these two factors interact rather than operating separately and in sequence as had been previously suggested.

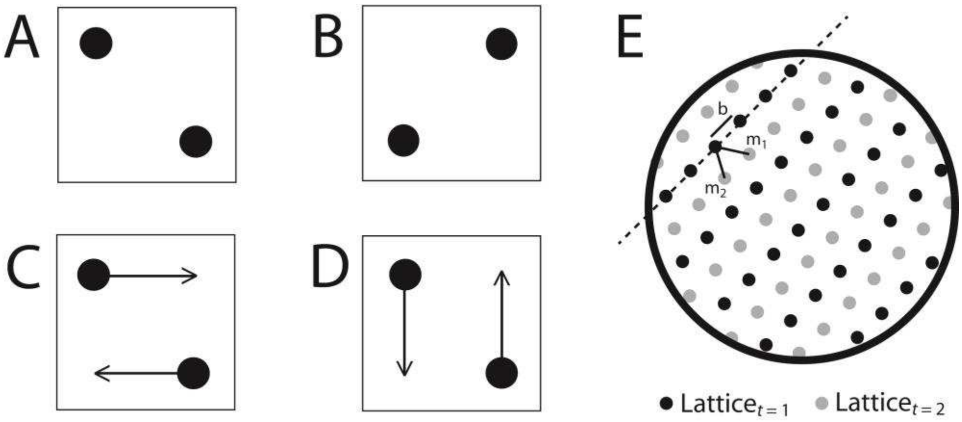

Figure 12. Apparent motion can occur when elements change position from one point in time (A) to the next (B). If more than one element is present this can lead to ambiguous motion direction. For instance, the change from pattern (A) to pattern (B) can occur either because of (C) horizontal motion of the elements or because of (D) vertical motion of the elements. (E) Two frames of a motion lattice are shown. $\mathit{Lattice}_{t=1}$ is shown in black and $\mathit{Lattice}_{t=2}$ is shown in gray. Spatial grouping along the dashed line (not present in displays) is modulated by the distance *b*. Temporal grouping is modulated by the ratio of distances m_1 and m_2 from an element in $\mathit{Lattice}_{t=1}$ to its nearest neighbours in $\mathit{Lattice}_{t=2}$.

The nature of the interaction between spatial and temporal factors in apparent motion, has been controversial with some results supporting the notion of *space-time coupling* whereas others support *space-time trade-off*. Coupling is present if, in order to maintain the same perception of apparent motion (i.e., perceptual equilibrium), increases in the time difference between two elements must be accompanied by a corresponding increase in the distance between them. In contrast, space-time trade-off occurs when increases in distance between elements (from one frame to the next) must be countered with a decrease in the time between frames in order to maintain the same perception of apparent motion. Although these two types of behaviour seem incompatible, they have recently been unified with a single function to explain them. Coupling occurs at slow motion speeds and trade-off occurs at fast motion speeds (Gepshtein & Kubovy, 2007). This unification provides a coherent account of the spatio-temporal factors that affect grouping (and apparent motion) in discrete dynamic patterns.

3. Top-down /non-image factors

3.1. Probability

In the RDT paradigm, participants are faster at detecting two repeated-colour (or another repeated property) targets within an alternating-colour array when the targets appear within the same group than when they appear between two groups as indicated by a grouping principle such as common region (Palmer & Beck, 2007). In the typical version of this task, targets are equally likely to appear within groups and between groups across all of the trials of the experiment. In this case, using grouping by proximity, common region, or another factor is equally likely to help or hinder finding the target. However, in a situation in which targets are between groups on 75% of trials, the perceptual organisation provided by grouping would actively hinder performance in the task. In an experiment which varied the probability of the target appearing within the same group (25%, 50% or 75%), participants were sensitive to this manipulation and could even completely eliminate the disadvantage of between-group targets with the knowledge of what type of target was more likely (Beck & Palmer, 2002). A key question about this effect is what mechanism mediates it. One interpretation is that the participants can use probability as a grouping principle and this can itself compete against other grouping principles and results in a different perceived grouping in the display. Alternatively, it could be that participants intentionally change their response strategy or allocate attention differently according to the probability knowledge. In this case, there may be no actual change in *perceived* grouping but the effects of perceived grouping may be overcome by a compensating strategy. This is a difficult question that is not easy to answer. However, it is clear that, at the very least, probability manipulations can at least overcome and affect the results of grouping on performance. It is also unclear the extent to which participants need to be aware of the probability manipulation in order for it to be effective.

3.2. Learning, associative grouping, and carryover effects

Grouping principles have generally involved relationships between the image features of elements at the time grouping is occurring. Very little attention has been paid to how learning from previous visual experiences can impact visual grouping. Recently, Vickery and Jiang (Vickery & Jiang, 2009) investigated this issue. They repeatedly presented participants with pairs of unique shapes (Figure 13A and 13B) that were grouped within a common region (see Common Region section above). During this training phase, a given shape always appeared as grouped with the same other shape. To assess the effectiveness of this grouping during the training phase, the authors used the RDT (Palmer & Beck, 2007). Participants had to detect a target pair of adjacent shapes that had the same colour. As expected, participants were faster at this when the target pair occurred within the same group (Figure 13A) than when the two elements of the target pair were in different groups (Figure 13B). This confirmed that the participants were perceiving grouping by common region in the training phase. After 240 trials of training on these shapes, the participants then saw the same pairs of shapes but now without the surrounding contours (Figure 13C). Based on image factors alone, these stimuli should not be subject to any grouping. Instead, the authors found that participants were significantly faster at detecting the target pair when it appeared within one of the previously seen groups (Figure 13C) than when the pair was between two previously learned groups (Figure 13D). This suggests that association between shapes based on their previously observed likelihood to appear together, can cause grouping of those shapes in later encounters. Importantly, the task at hand was not dependent on the shapes and only required participants to attend to the colours of the shapes. The authors termed this effect *associative grouping*. In another study, they found that associative grouping also caused shapes to appear closer together than shapes that had no association history, an effect that mimics previously-observed spatial distortions induced by grouping (Coren & Girgus, 1980). Other results have also suggested that previous experience, both short term and lifelong, can have effects on the outcome of perceptual grouping processes (Kimchi & Hadad, 2002; Zemel, Behrmann, Mozer, & Bavelier, 2002).

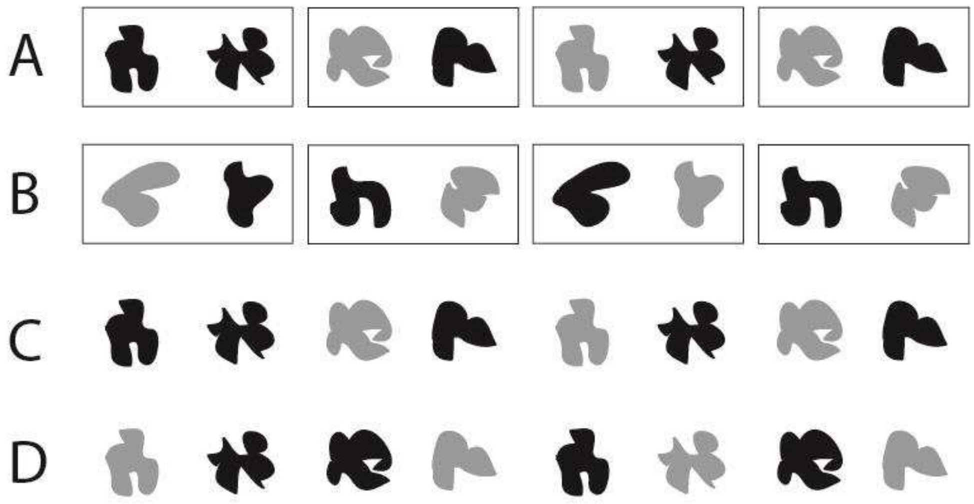

Figure 13. Example stimuli from Vickery & Jiang (2009). Participants saw shapes of alternating colours in a row and had to determine the colour of a target pair which was a pair of adjacent shapes with the same colour, i.e. RDT paradigm. Black is the target colour in this example. (A) During the training phase participants saw the shapes grouped into pairs by common region using outline contours. In some cases the target appeared within the common region group. (B) In other cases, the target appeared between two common region groups. (C) After training participants saw the same stimuli paired as they were during training but without the region outlines. The target could appear within the previously-learned group or (D) between learned groupings.

Some effects of previous experience on grouping are much more short-lived and may derive from the immediately preceding stimuli. Hysteresis and adaptation are well-known carryover effects on visual perception. *Hysteresis* is the tendency for a given percept to persist even in contradiction to sensory evidence moving in the opposite direction, i.e., it maintains the status quo. *Adaptation*, on the other hand, reduces sensitivity to the stimulus features at hand and thus reduces their influence on subsequent perceptual decisions. Gepshtein and Kubovy (2005) demonstrated that both of these processes have effects on perceptual grouping and, moreover, the two influences operate independently of one another. They showed participants dot lattices (Kubovy & Wagemans, 1995) with two competing organisations, e.g., along directions *a* or *b* (Figure 2C). As with previous work, they varied the proximity along these two dimensions and found the expected effects of proximity on grouping. In a further analysis, they then split the data into trials on which the participant perceived grouping along a, for instance, and determined the likelihood that the participant would grouping along a in the next stimulus. Participants were significantly more likely than chance to grouping along the same direction as the preceding stimulus. This demonstrates an effect of hysteresis on perceptual grouping. They also found that the probability of perceiving grouping along one dimension, say *a*, in a stimulus decreased with stronger perceptual evidence for it in the preceding stimulus (i.e. greater proximity along *a* in the previous stimulus). This was true regardless of whether you saw grouping along *a* or *b* in the preceding stimulus. The authors interpreted this as evidence for adaptation. Essentially, when an observer sees strong evidence for grouping along one dimension in a stimulus, the visual system adapts to this evidence, making the system less sensitive to that same evidence for grouping when it appears in the next stimulus. Although the recent data described above has clarified the nature of these carryover effects, hysteresis, for instance, was not unknown to Wertheimer and he described it as the factor of *objective set* (1923).

4. Theoretical issues about grouping

In addition to identifying new grouping principles, a significant amount of modern work on perceptual grouping has focused on theoretical issues about grouping. A major issue has been to understand how grouping fits amongst all of the other processes of visual perception. Does it occur very early without any input from later processes (e.g., attention, object recognition) or does it interact with these processes to determine its results. Alternatively, grouping may occur throughout visual processing or there may be several fundamentally different types of grouping which rely on independent mechanisms and have their own time-courses. Alongside the development of new principles, modern vision scientists have also worked to address some of these theoretical issues that place grouping in context and try to reveal the mechanisms that generate their phenomenal consequences and effects on task performance. Below are two examples of these theoretical issues.

4.1. When does grouping happen?

Information processing approaches to vision have typically tried to determine the sequence of processing operations that occur within the visual system (e.g., Palmer & Rock, 1994). Neurophysiological approaches suggest a hierarchy of visual areas (Felleman & Van Essen, 1991), albeit with significant amounts of bidirectional communication between areas. Where does perceptual grouping occur in these processing structures? Classically, grouping principles were considered to operate relatively early in models of visual processing because they were based on simple image characteristics that can be computed directly from the image. However, “early” is not well-defined. To address this issue, Rock and Brosgole (1964) aimed to determine whether grouping occurred before or after a particular reference point in visual processing, i.e., the construction of three-dimensional scene representation. To do this, they constructed a two-dimensional array of luminous beads (Figure 14A). In one condition, they presented this array to participants in a dark room perpendicular to the line of slight (Figure 14B). Based on proximity, this array tends to be perceived as columns. However, in another condition, the array of beads was tilted in depth (Figure 14C). The tilt caused a foreshortening and thus in two-dimensional (2D) image coordinates the elements became closer together in the horizontal dimension which should make grouping by proximity more ambiguous. Of course, in three-dimensional (3D) image coordinates, the beads remained closer together vertically. If grouping is based on a 3D representation, then the participants should see columns based on the shorter 3D vertical distances between elements. Alternatively, if grouping is based on the 2D representation, then they may be more likely to see rows. When viewing the arrays with both eyes opened (and thus full 3D vision), participants grouped according to the 3D structure of the displays. However, when participants closed one eye and saw only the 2D image information, they were more likely to group the display into rows based on the 2D proximity of elements caused by foreshortening. Similar effects have been shown for similarity grouping suggesting that grouping by lightness (Rock, Nijhawan, Palmer, & Tudor, 1992) occurs on a post-constancy representation of visual information. Other work has shown that grouping can also be affected by the outcome of interpolation processes such as modal (Palmer & Nelson, 2000) and amodal completion (Palmer, Neff, & Beck, 1996). All of these results suggest that grouping occurs on a representation beyond simple image features. Furthermore, grouping also seems to be able to affect the results of figure-ground processing (Brooks & Driver, 2010; Palmer & Brooks, 2008) contradicting previous proposals that grouping can only occur after figure-ground organisation (Palmer & Rock, 1994). Although much of the evidence above suggests that grouping occurs later in visual processing than previously thought, it does not always do so. Grouping by colour similarity is based on a post-constancy representation with long duration displays, but when presented for very brief periods these displays are grouped by pre-constancy features (Schulz & Sanocki, 2003).

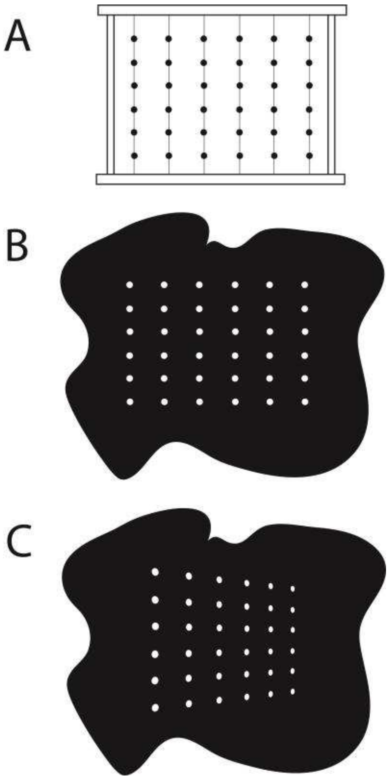

Figure 14. Adapted from Figure 6.1.12, page 264, Palmer (1999). (A) The array of luminous beads used by Rock and Brosgole (1964) aligned in the frontal plane with support structure. The luminous beads appeared in the dark either in the (B) frontal plane or (C) tilted in depth.

Another approach to this question has been to assess whether perceptual grouping occurs pre-attentively or only within the spotlight of attention? An early study on this issue used an inattention paradigm (Mack, Tang, Tuma, Kahn, & Rock, 1992). As with many other studies of grouping, arrays of shapes that could be seen as arranged either in rows or columns (e.g., see Figure 4) were presented to participants. However, in this case, a large cross was overlaid between the central rows and columns and participants were instructed to focus their attention on it and judge whether the horizontal or the vertical part of the cross was longer. Despite the array of elements being in the centre of the participants' visual field during this task, they were unable to report whether the array was grouped into rows or columns. Presumably, this is because they were not attending to the grouping array while their attention was focused on the task-relevant cross. This was taken as evidence that even if a pattern is at the centre of vision, grouping processes may not operate unless attention is specifically allocated to the pattern (also see Ben-Av, Sagi, & Braun, 1992). However, since then, others, using different paradigms, have uncovered evidence, often indirect, that at least some perceptual grouping may be operating pre-attentively (Kimchi, 2009; Lamy, Segal, & Ruderman, 2006; Moore & Egeth, 1997; Russell & Driver, 2005), although this is not the case for all types of grouping (Kimchi & Razpurker-Apfeld, 2004).

All of these results together have been taken to suggest that grouping may occur at many different levels of processing rather than being a single step that occurs at one point in time (Palmer, Brooks, & Nelson, 2003). Furthermore, different types of grouping may occur at different levels. It is also possible that at least some grouping is dependent on recurrent processing between different levels, or brain areas, rather than representing single sequential steps (e.g., Lamme & Roelfsema, 2000; Roelfsema, 2006). This is an issue that is just starting to be addressed systematically and may most directly be approached by studying how perceptual grouping is implemented in neural circuits.

4.2. Mechanisms of grouping

One well-known mechanism that may underlie perceptual grouping is suggested by the *temporal correlation hypothesis* (Singer & Gray, 1995; von der Malsburg, 1981) which holds that synchrony in neural populations serves as a binding code for information in different parts of cortex. Grouping may be mediated by synchronization of activity between neurons representing different elements of a group. Although some neurophysiological recordings in animals (e.g., Castelo-Branco, Goebel, Neuenschwander, & Singer, 2000; Singer & Gray, 1995) and EEG recordings in humans (e.g., Tallon-Baudry & Bertrand, 1999; Vidal, Chaumon, O'Regan, & Tallon-Baudry, 2006) have supported this idea, it remains a controversial hypothesis (e.g., Lamme & Spekreijse, 1998; Roelfsema, Lamme, & Spekreijse, 2004). Much of that evidence applies to limited types of grouping such as collinearity/continuity (e.g., Singer & Gray, 1995) or formation of illusory contours based on these features (e.g., Tallon-Baudry & Bertrand, 1999). It is not clear whether synchrony can serve as a general mechanism to explain a wider array of grouping phenomena, especially those not based on image features. For more discussion of the role of oscillatory activity in perceptual organization see Van Leeuwen's Cortical Dynamics chapter (this volume). Van der Helm's Simplicity chapter (this volume) discusses a link between synchrony and perceptual simplicity.

Even if multiple cues do use synchrony as a coding mechanism, it may be that different cues use different parts of visual cortex or recruit additional mechanisms. However, some fMRI evidence suggests that proximity and similarity grouping cues, for instance, share a common network including temporal, parietal and prefrontal cortices (Seymour, Karnath, & Himmelbach, 2008). In contrast, some ERP evidence has shown differences in the time-course of processing of these two grouping cues (e.g., Han, Ding, & Song, 2002; Han, Song, Ding, Yund, & Woods, 2001) and other cues (e.g., Casco, Campana, Han, & Guzzon, 2009). Other work has focused specifically on interactions between different visual areas with the role of feedback from higher order areas a critical issue (Murray, Schrater, & Kersten, 2004). A significant amount of computational work has also generated specific models of perceptual grouping mechanisms. For instance, some of this work has aimed to explain how grouping effects may emerge from the structure of the laminar circuits of visual cortex (e.g., Grossberg, Mingolla, & Ross, 1997; Ross, Grossberg, & Mingolla, 2000). A full review of findings on neural and computational mechanisms of grouping is beyond the scope of this chapter but it is clear that even with the simplest Gestalt cues there is evidence of divergence in mechanisms and many competing proposals.

4.3. Prägnanz and simplicity

Wertheimer (1923, 2012) dedicated a relatively large section of his article to discussing and demonstrating that a particular organization of elements may be favoured because it is "better" than other organizations, i.e. a good Gestalt. This idea has been called the law or principle of *Prägnanz* (German word meaning "conciseness") and the notion received substantial attention from Gestalt psychologists other than Wertheimer (Koffka, 1935; Köhler, 1920). For instance, the lines in Figure 15A could be perceived as edges 1 and 2 forming one object and lines 3 and 4 forming another object (as shown in Figure 15B). However, most people do not see this organization. Instead, they perceive two symmetrical objects that are overlapping (shown non-overlapping in Figure 15C). Wertheimer claimed that the organization in Figure 15B produces "senseless" shapes which are not very good Gestalts or whole forms. Those produced by the organization represented in Figure 15C form better wholes. Notice that in this case, this means that we follow what seems to be a factor of good continuation in grouping the edge segments together rather than closure which may have favoured the other organization. Wertheimer seemed to suggest that ultimately all of the factors that he proposed are aimed at determining the best Gestalt possible given the stimulus available. Furthermore, competitions amongst them may be resolved by determining which of them produces the best Gestalt.

Although the idea of Prägnanz was relatively easy to demonstrate, a clear, formal definition was not provided by the Gestaltists. To fill this gap, modern vision scientists have often framed the problem in terms of information theory. In this framework, organizations of the stimulus that require less information to encode them are better than those which require more information (Hochberg & McAlister, 1953). For instance, symmetrical figures (Figure 15C) may require less information to encode than similar non-symmetrical figures (Figure 15B) because one half of each figure is a simple transformation of the other. This could reduce the information needed to encode them by nearly one half if you encode it as two identical halves plus one transformation. There are multiple versions of how stimuli can be encoded, their information measured, and simplicity compared (e.g., Collard & Buffart, 1983; Garner, 1970, 1974; Leeuwenberg, 1969, 1971).Regardless of how it is computed, if visual system uses simplicity as a criterion for determining perceptual structure, it is presumably useful in terms of constructing an evolutionarily useful representation of the physical world. However, there is no guarantee that simple representations are actually veridical. For a more detailed discussion of these important issues see van der Helm’s chapter on Simplicity in this volume.

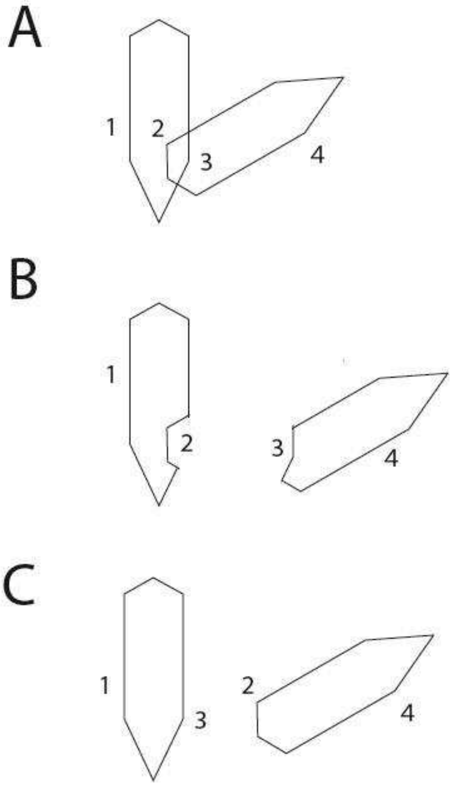

Figure 15. The principle of Prägnanz. (A) The four edge sections 1-4 can be seen as arranged into different structures. Edges 1 and 2 may group to form an object separate from 3 and 4 which form another object as represented in panel (B). Alternatively, edges 1 and 3 may join and 2 and 4 join to form better shapes like those depicted in panel (C).

5. Summary

The Gestalt psychologists discovered and popularised an enduring set of grouping principles. Their methods were largely based on demonstrations. To some, this has been seen as a point of weakness. However, the ability to see clear effects through demonstration alone actually shows the strength of the effects that they found, especially in comparison to some modern indirect methods which only show effects, for instance, on the order of tens of milliseconds. Modern vision scientists have elaborated some of these principles by studying them quantitatively and clarifying the conditions under which they operate. However, some of the original principles still are without clear formal definitions (e.g., good continuation) and work needs to be done on this. There has also been significant work on how different principles combine (Claessens & Wagemans, 2008; Elder & Goldberg, 2002), an important issue given that natural images often seem to contain many cues simultaneously. A robust set of new principles have also been articulated. Many of these involve dynamic scene features and others highlight the influence of context, learning, and other aspects of cognition. Although all of these principles can be termed as grouping based on their phenomenological effects, such a diverse set of image-based and non-image factors are likely to involve a wide range of different neural mechanisms. Identifying the mechanistic overlap between different principles is an issue, that when addressed, will shed greater light on how we might further categorize them. It is also unlikely that the principles described above form an exhaustive list. The brain likely picks up on many sources of information in visual scenes to drive perceptual grouping and we have likely only scratched the surface.

6. References

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