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Texture Density Adaptation and the Perceived Numerosity and Distribution of Texture

Frank H. Durgin
University of Virginia

Three experiments were conducted to assess the impact of adaptation to dense visual texture on the perceived numerosity and spatial distribution of texture. Study participants compared fields of dots presented in 2 locations, 1 of which was adapted to dense arrays of dots. The effect of adaptation was assessed by measuring points of subjective equality between the adapted and unadapted regions for the perceived density, numerosity, and distribution (cluster) of texture with staircase procedures for textures containing 20–320 dots. Perceived texture density was reduced at all numerosities. For high numerosities, density adaptation markedly diminished the perceived numerosity but not the apparent cluster of the dots. At low numerosities, the opposite pattern of results emerged, suggesting that density is more influential in the perception of high numerosities and that perceptual distortions of number and cluster may be traded off with one another. A simulation study of Allik and Tuulmets's (1991) occupancy model of perceived numerosity is also presented, and suggestions are made for modifying the model based on the patterns of results found.

An important part of our visual experience of objects derives from the textures of their surfaces. Texture can inform us about the material composition of an object and thus about its nature. Though some textures—like woven fabrics and window screens—have regular patterns, most textures are irregular, having no constant or precisely predictable spatial distribution. As a result the representation of irregular textures is informationally intense: Unlike a regular pattern, it is difficult to summarize the spatial texture information of a leopard's fur or a cinder block surface without sacrifice of detail. Although our perceptual experience of visual textures involves a subjective sense that no detail is lost, it is likely that our perceptual experience is based on a multitude of overlapping but discrete pieces of summary information that mutually constrain what we end up perceiving. Direct evidence of perceptual interpolation is seen in the work of Ramachandran and Gregory (1991), for example, in which dynamic-noise patterns are completed or filled-in across cortical "blind spots." Although Ramachandran (1992) proposed that appropriate visual neurons are actually activated when this happens, the (subjectively) detailed visual information they are "registering" is clearly a kind of abstract summary. What is its content?

Frank H. Durgin, Department of Psychology, University of Virginia.

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Correspondence concerning this article should be addressed to Frank H. Durgin, who is now at the Department of Psychology, Swarthmore College, Swarthmore, Pennsylvania 19081. Electronic mail may be sent via Internet to fdurgin1@cc.swarthmore.edu.

If some detail is "lost" in the perception of complex textures, what information does get represented? We can examine the perceptual representation of the spatial information in irregular textures using scatter-dot displays, such as Figure 1. Although these simple achromatic displays are not typically found in our environment, they enable us to examine the perception of spatial texture attributes in isolation from other important properties of surfaces such as luminance, chroma, and spatial frequency.

What do we see when we look at scatter-dot textures? The panels of texture in Figure 1 differ along two distinct and salient dimensions: (1) It is evident that the panels differ from left to right in the apparent number of dots (*numerosity*), and (2) the dots in the upper fields appear more irregularly spaced, or more *clustered,* than those in the lower fields. Our ability to appreciate these differences indicates that the visual system recovers sufficient information to represent both of these dimensions. Compare the ease with which these observations may be confirmed with the difficulty involved in determining that the upper-right field is actually a subset of the upper-middle field (i.e., all of the dot locations of the right field are present in that middle field), which is in turn a subset of the upper-left field. Verification of this relationship requires painstaking examination of each small group of dots individually. Your perceptual representation of the upper panels contains easily accessed information about the relative numerosity and cluster of the dots but not about subset relationships.

The perception of both numerosity and cluster may derive from the perception of texture density. *Texture density,* the number of elements per unit of area, is the simplest descriptive statistic of a texture field and is readily used for surface segregation (Barlow, 1978; Marr, 1982). Although density is defined as if it were derived from number and area, it might just as easily be defined as some function of area per

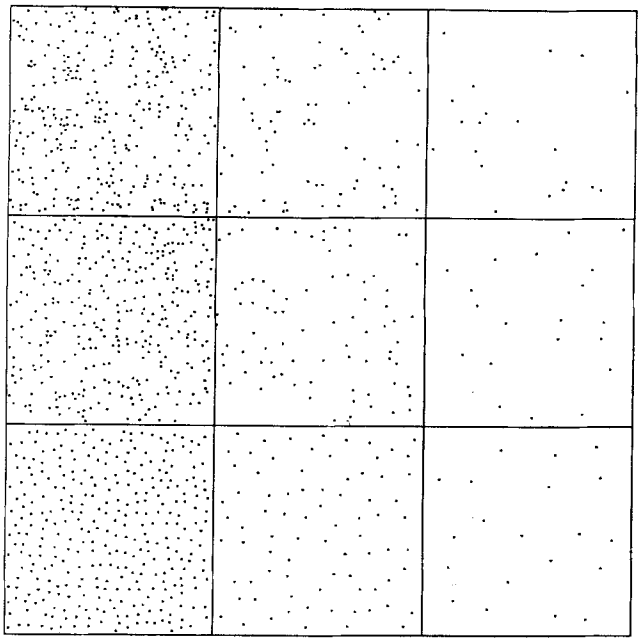


Figure 1. Textures that differ from left to right in number and from top to bottom in cluster. Across each row, each field contains 320, 80, or 20 dots, respectively. Textures were made to differ in level of cluster by manipulating the minimum interdot distance (MinID) allowed in the texture generation process (described in Experiment 2).

dot or interdot distances. It is therefore plausible that the perception of numerosity entails the integration of texture density over area. In addition, cluster can be defined as a measure of the variance of densities present in a texture (Ginsburg & Goldstein, 1987) and is thus also derivable from what might be termed *density information.* Note that both density and cluster are expressions of the spatial distribution of texture elements according to this analysis; one represents the mean and the other the variance.

In the present article, I use aftereffects resulting from the adaptation to dense texture to examine the perceptual representation of texture density, numerosity, and cluster. Visual aftereffects—distortions of perception produced by perceptual adaptation—are ubiquitous in perception and provide a window on perceptual and visual representation. Aftereffects are known to affect perceived color (Hering, 1920/1964), depth (e.g., Blakemore & Julesz, 1971), location (Köhler & Wallach, 1944), motion (Wöhlgemuth, 1911), orientation (Gibson & Radner, 1937), and spatial frequency (Blakemore & Sutton, 1969). Thus, aftereffects are found for dimensions for which neural "detectors" are thought to exist, and adaptation paradigms are frequently used to investigate the nature of hypothesized information-analysis systems (cf. Graham, 1989, for a review of research on spatial frequency adaptation).

Perceived texture density is subject to a strong aftereffect, suggesting the visual primacy of density: Adaptation to dense visual texture produces a decrease (by as much as a factor of two) in the perceived density of texture presented later to the same region of the visual field (Durgin & Proffitt, 1991). This aftereffect is illustrated in Figure 2 and may be experienced directly by the following procedure: Fixate on the cross-hair of Panel A of Figure 2. After several seconds move your gaze to the fixation mark of Panel B. For most observers, the right (adapted) texture of Panel B will now appear less dense than the left texture, though the two are identical textures (radially symmetric about the fixation mark). The textures of Panel C illustrate textures that might appear equal in numerosity after adaptation; they are based on the results of the experiments that follow.

In the current article texture density adaptation is found to produce different phenomenal distortions of texture at different texture densities. Although judgments of texture density itself are uniformly and strongly distorted at all levels of density, the effects of adaptation on numerosity and clustering judgments appear to be range dependent and reciprocal: For textures with numerous elements, adaptation reduces the apparent number of texture elements but does not distort their apparent cluster. For low-density textures, nu-

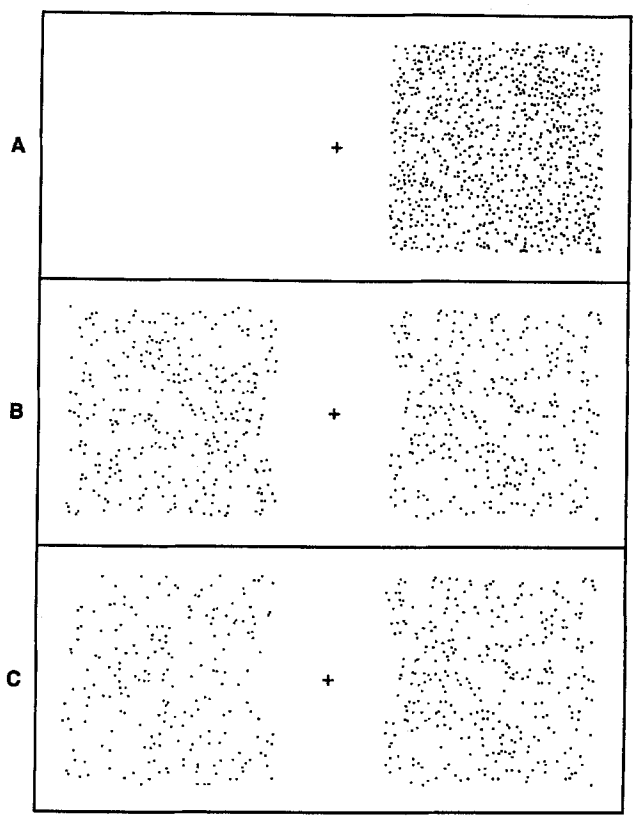


Figure 2. Scatter-dot textures like those used for texture density adaptation. Panel A illustrates an adaptation stimulus with fixation mark. Panel B shows test fields that are objectively equal in density. Panel C represents fields that might appear subjectively equal in their numerosity after adaptation to the upper panel (the numerosities shown represent the means of the data from the current experiments: 320 dots in an adapted region were perceived equal in numerosity to 224 dots).

merosity suffers only slight distortion, but a large change is found in the apparent cluster of texture elements.

On the basis of these phenomena, I will argue that texture density has a special role in the visual analysis of texture. I will also argue that the perceptual representation of cluster, density, and numerosity may be constrained by their conceptual and perceptual interdependence. For example, it is reasonable that perceived numerosity would be affected by a distortion of perceived density; however, it is not clear why the effects on numerosity, but not density, might be range dependent. It is possible that density information is influential in the perception of high numerosities but that other sources of numerosity information are more important at lower numerosities. Because this notion is somewhat at odds with current models of the perception of numerosity (e.g., Allik & Tuulmets, 1991) and because this research has important implications for the perceptual representation of density and cluster as well, I will briefly review the literature on numerosity, density, and cluster perception.

Numerosity Perception

Numerosity: One or Many?

The perception of numerosity has been the focus of several lines of investigation. The earliest work on perceiving numerosity (Jevons, 1871) showed that there was a limit on the number of items one could immediately and accurately enumerate. Jevons wished to determine the number of items that could be simultaneously held in consciousness, a concern that has a more sophisticated modern successor in investigations of the number of independently moving elements that can be tracked (attended) simultaneously (e.g., Pylyshyn, 1988).

Taves (1941) and Kaufman, Lord, Reese, and Volkmann (1949) furthered the work of showing that there seemed to be different regimes of numerosity perception, which Kaufman et al. labeled *subitizing* (the immediate, accurate assessment of small numbers of elements—less than about five or six), and *estimating*. Further refinements of this work distinguished subitizing from counting on the basis of response latencies and error rates of number naming (Mandler & Shebo, 1982; Minturn & Reese, 1951). For example, using 200-ms exposures, Mandler and Shebo found that for one to three items, there are essentially no errors in the identification of number and only a slight increase in response time (about 50 ms) per item. From four to nine items, the error rate increases linearly to reach nearly 100% (due to underestimation), and the response latencies also increase by about 200 ms per item. Trick and Pylyshyn (1993) have shown that elements that can be segregated from distractor items by preattentive processing can be subitized.

It seems clear that a serial counting process (probably requiring moving the focus of attention according to Trick & Pylyshyn, 1993) can be distinguished from subitizing, but it remains controversial whether subitizing involves a special visual process that distinguishes it from the (albeit inexact) immediate impression of numerosity, which is found with higher numerosities and apparently underlies estimation. From a psychophysical point of view, both response latencies and response error should increase as the perceptual discriminability of a stimulus decreases (Averbach, 1963). When counting is prevented, correctly identifying six items involves rejecting both five and seven, and these are both perceptually more similar to six than is one or three to two. van Oeffelen and Vos (1982) argued that if perceived numerosity were considered a log-linear function, then low errors and short latencies could also be expected in the discrimination of higher numerosities, such as 15 from 20, when the study participant's response set was appropriately limited. These predictions were indeed borne out. The force of this argument is that both response latency and response accuracy of numerosity judgments in the subitizing range may reflect high perceptual discriminability (essentially a floor effect), facilitating a quicker and more accurate decision process within a single visual dimension.

On the other hand, van Oeffelen and Vos (1982) did note that there is special configural information in dot representations of very low numbers like three and four (these can often be seen as a triangle and quadrilateral), which seems to give them added benefit in accuracy of recognition. Mandler and Shebo (1982) have developed the geometric-form argument for the numbers 1–3, and Wolters, van Kempen, and Wijlhuzien (1987) provided further evidence that pattern familiarity can account for the fairly flat latencies of the subitizing data. Such arguments could apply to the evaluation of preattentively segregated elements and even to seemingly anomalous patterns that can be subitized (e.g., three elements in a line can be subitized as quickly as in a triangle; Trick, 1987, as cited in Trick & Pylyshyn, 1993). Interestingly, a related observation has been made in the current literature on tracking multiple moving dots: More dots can be simultaneously tracked if their movements are confined such that they can be perceived as the vertices of a deforming polygon (Yantis, 1992).

Although the subitizing range of numerosity will not be explored in the experiments reported here, the question of whether there are different kinds of visual processes influencing perceived numerosity is a central concern. From the point of view of decision theory it is arguable that there is continuity between the perceptual information underlying subitizing and that underlying estimation. Subitizing could, according to this viewpoint, simply represent a range of perceptual numerosity "estimation" in which the answer is heavily overdetermined. What I wish to argue is that there is room for a compromise (or perhaps a synthesis): Special kinds of information may be of particular discriminatory value at various ranges of numerosity. As a result, numerosity judgments overall may be seen as deriving from a larger system that capitalizes on information derived from distinct sources, including such things as the attentional markers proposed by Pylyshyn (1988; Trick & Pylyshyn, 1993). Although, when viewed as a larger system, numerosity perception may be conceived as unitary, an underlying multiplicity may become evident when distinct perceptual processes are experimentally manipulated.

Numerosity as a Perceptual Magnitude

Research into the perception of greater numerosities has proceeded in two directions. On the one hand, judgments of numerosity have been shown to be susceptible to a variety of intriguing context effects and cognitive illusions including effects of figure–ground perception (Bevan, Maier, & Helson, 1963; Bevan & Turner, 1964) and contrast with expectancy produced by correlating numerosity and field size (Birnbaum & Veit, 1973). On the other hand, several researchers have investigated the psychophysical properties of numerosity perception as if numerosity were a simple visual dimension (Indow & Ida, 1977; Krueger, 1972, 1984).

The latter approach has been remarkably successful in demonstrating that magnitude estimations of perceived numerosity follow a power function over a range of numerosities extending from 20 to 1,000 (e.g., Indow & Ida, 1977; Krueger, 1972, 1984; although see Masin, 1983, for a different conclusion). However, these studies did not take into account the effects of cluster. It was known even from Taves's (1941) investigations that the spatial arrangement of dots affected the perceived numerosity. According to current research, dots in regular displays are judged more numerous than equal numbers of dots arranged irregularly (Ginsburg, 1976, 1978; Ginsburg & Goldstein, 1987). Although Ginsburg (1978) conjectured that this was due to a cognitive interaction between the dimensions of numerosity and regularity, Ginsburg and Goldstein (1987) have reported a failure to support this hypothesis with a direct test.

The effects of spatial distribution have led in recent years to the development of models of numerosity perception that were based on the notion that regular arrays "filled" space better than clustered, irregular arrays. Illusions of extent, such as the Mueller–Lyer illusion and the Ponzo illusion, also affect perceived numerosity (cf. Luccio, 1983, for a review). van Oeffelen and Vos and colleagues (van Oeffelen & Vos, 1983; Vos, van Oeffelen, Tibosch, & Allik, 1988) noted that numerosity judgments were correlated with some sense of filled area and offered some qualitative illustrations of how an area-based model could predict certain effects of dot distribution. However, a quantification of the effects of dot distribution was not carried out until Allik and Tuulmets (1991) demonstrated that a surprisingly simple area-based "occupancy" model accounted very well for numerosity judgments of dot fields that were systematically varied in their spatial arrangement.

The occupancy model (Allik & Tuulmets, 1991) supposes that the total area occupied by a texture may be quantitatively modeled by surrounding each texture element with a circular patch of radius *R*. By manipulating the spatial distribution of dots (along a cluster dimension like that illustrated in Figure 1), Allik and Tuulmets determined that for fields of 20 and 40 dots, numerosity discrimination could be predicted by the total area of the display that was filled by such patches. This total area is referred to as the *occupancy index*. If two dots were close to one another, their occupancy patches overlapped, resulting in a lower occupancy index (see Figure 3).

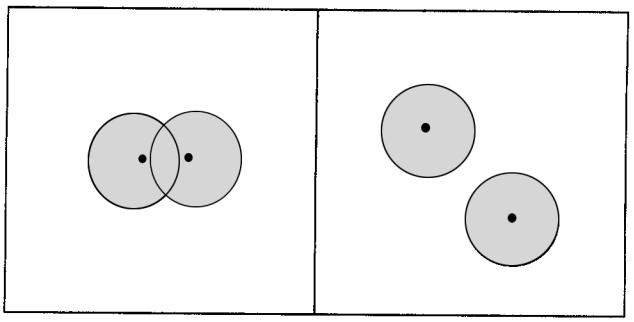


Figure 3. The basic principle of the occupancy model (after Allik & Tuulmets, 1991): Dots are hypothesized to occupy a region (shaded) of radius *R*. Perceived numerosity is determined by the total area occupied by dots. When dots are closer than 2*R*, their occupancy patches overlap, resulting in a lower perceived numerosity.

The value of *R* that Allik and Tuulmets (1991) calculated from their data was about 0.33° of visual angle (20′). Though such a large radius is reasonable when densities are as low as 40 elements in a 4° × 4° field, it is easy to construct figures for which that value of *R* fails: In Figure 4 the densities of the two fields are substantially different, but in both displays the areas are completely filled according to the occupancy model, and only the relative size (total area) of the fields should be informative about numerosity.[1] Allik and Tuulmets suggest that *R* must be variable, but do not explain how their model is to accommodate a variable *R*. A premise of their argument is that perceived numerosity is identical to the occupancy index and thus to filled area, but the occupancy index from which numerosity is derived is a function of *R*. Therefore, the calculation of numerosity from the occupancy index requires that *R* be "known" to the visual system. If *R* is varied, what specifies the size of *R*? Some correlate of dot density? If so, then a representation of dot density has crept into the occupancy model of numerosity unannounced, and the claim that perceived numerosity is the same as occupied area is misleading. In short, although the occupancy model represents an elegant and important formulation of the perception of numerosity, it would seem that a model that assumed multiple sources of information about numerosity is required and that such a model is latent in the notion of a variable *R*. At present, the occupancy model emphasizes the importance of area; the role of texture density information will be examined here.

Texture Density

In his classic study on the efficiency of density discrimination, Barlow (1978) suggested that there were four dif-

[1] Allik and Tuulmets (1991; Allik, Tuulmets, & Vos, 1991) suggested that the area occupied by a dot may be better expressed relative to the total area of the display, in which case they offer a value of 2.2%. This does not avoid the problem of displays becoming full, however: Assuming a fairly even random distribution of elements within a fixed region, the occupancy index of a display of 400 dots would not differ from that of a display of 800.

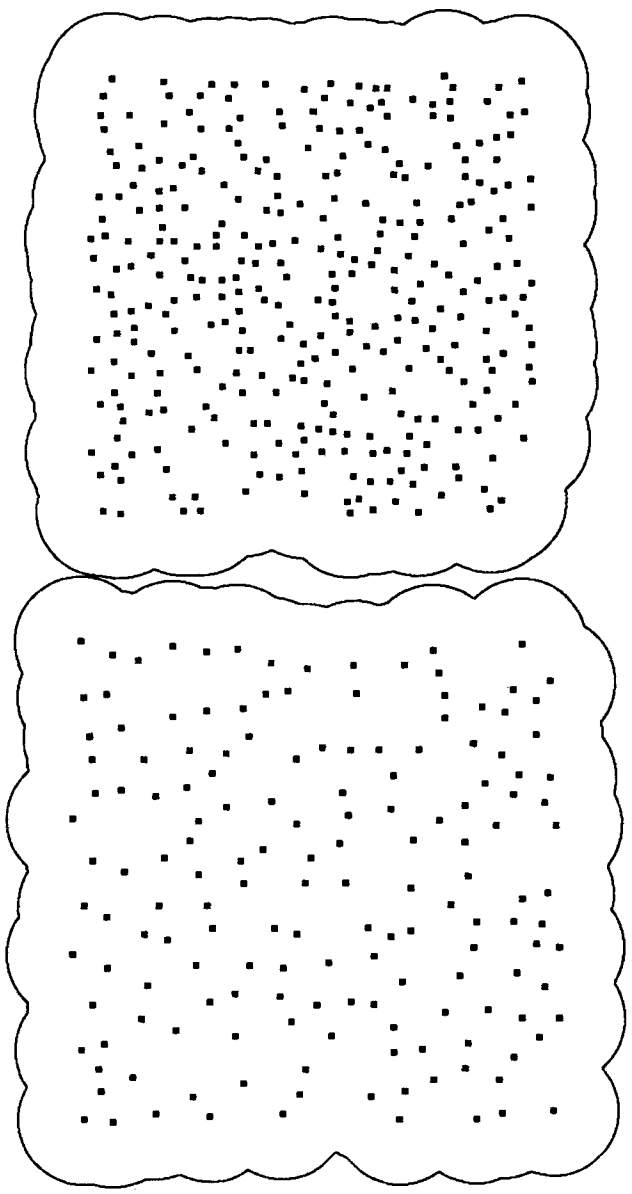


Figure 4. Stimuli for which the occupancy model (Allik & Tuulmets, 1991) fails: For empirically determined values of *R*, the occupancy model predicts that the lower field should appear more numerous from a normal viewing distance (occupied area is outlined). The occupancy model was derived with low numerosities and is not sensitive to the density information in these textures. The upper field contains 320 dots, the lower field 160.

ferent kinds of subjective judgments depending on the level of numerosity and density. In addition to judgments based on seeing accurately the actual number of dots or subitizing (at the low end of the range) and those based on overall brightness (when dot density was quite high), Barlow suggested that there was another subjective distinction between numerosity judgments (for low numerosities beyond the subitizing and counting range) and discriminations based on "texture, dot density, or average dot separation" (for higher numerosities; p. 644). Mulligan and MacLeod (1988) have reported that fluctuations in dot brightness and dot density can be traded off against one another (in rectangular lattices of dots), indicating, among other things, an interaction between brightness and perceived density. However, Barlow's subjective distinctions have not otherwise received empirical confirmation implicating distinct visual processes. For example, Burgess and Barlow (1983) found that the precision of numerosity judgments was unaffected by the density of the dots (cf. also Allik, Tuulmets, & Vos, 1991). Thus, psychophysical research has been able to regard all levels of numerosity as a continuous scale and even to propose plausible explanations that eliminate the distinction between subitizing and estimating number, as discussed above.

However, a continuous psychophysical function of numerosity could result from the combination of several different kinds of relevant visual information that, though weighted differently at different levels of numerosity, interact or blend together to form a continuous scale. The present experiments will use the texture density aftereffect to provide empirical evidence for Barlow's (1978) distinction between texture density and other sources of information in the perception of numerosity. In addition, a simulation of the occupancy model of numerosity perception will be presented in the General Discussion, providing further support for this point of view.

I have already described the procedure for generating a texture density aftereffect (see Figure 2 and previous text). Durgin and Proffitt (1991) found that the aftereffect size for texture density perception (expressed as the ratio between subjectively matched and actual density after adaptation) was roughly constant for all densities tested. The stimuli they used were composed of fixed-size balanced dots (cf. Carlson, Moeller, & Anderson, 1984) to control for luminance and spatial frequency. It is noteworthy that Durgin and Proffitt used very large texture fields in which the total number of dots exceeded 200 even for the lowest densities. The present study was motivated by the informal observation that when numerosity is low (less than about 100), the density aftereffect does not seem to substantially affect the apparent number of dots, although a strong distortion of apparent density remains.

This observation, which concurs with Barlow's (1978) suggestion that the perception of low and high numerosities may differ, is not consistent with Allik and Tuulmets's (1991) occupancy model. Might it be that density and area (occupancy) information are combined in numerosity perception, and each source of information is weighted according to its relative sensitivity for discrimination? If so, Allik and Tuulmets's findings may be limited to a range within which density information is not influential in perceiving numerosity. Before proceeding to the experiments intended to demonstrate this possibility, let us consider one more related observation.

Perceived Cluster

Interestingly, along with the lack of distortion of numerosity, I noted a reduction in the apparent cluster of the

low-numerosity fields after texture density adaptation, a phenomenon I had not observed with higher numerosities. Ginsburg and Goldstein (1987) have suggested that *cluster*, defined as the variance of density, is a distinct perceptual dimension and have shown that discriminations can be made on that dimension. Anstis and Ho (1992) have recently reported a decrease in apparent cluster produced by adaptation to irregular texture. They argued that "disorder" is an adaptable perceptual dimension. However, because perceived cluster is related to variance of density, differences in perceived cluster might arise from distortions of density itself. For example, the low-density, high-cluster texture shown in the upper right panel of Figure 1 contains both small and large interdot distances—this is what classifies it as a high-cluster stimulus. If cluster were determined by estimating the variability of the densities that are apparently present in a texture, a reduction of the apparent cluster of a low-density field after adaptation to high texture densities could arise directly from a suppression of perceptual response to the smaller interdot distances (higher densities) in the low-numerosity texture.

Alternatively, even if cluster is not derived directly from density information, it is still perceptually linked to numerosity perception, as discussed previously. If the texture density aftereffect distorts the density but not the numerosity of a low-numerosity field, then a distortion of apparent cluster might serve as a kind of perceptual resolution of the conflict between density and other sources of numerosity perception. The attenuation of higher densities (small interdot distances) without an attendant loss of apparent numerosity is consistent with a display in which cluster is reduced (see, for example, the lower panels of Figure 1). I will return to these ideas in the *Discussion* of Experiment 2.

Overview of Experiments

The stimuli used by Durgin and Proffitt (1991) in their investigation of the texture density aftereffect did not cover the range of stimuli used by Allik and Tuulmets (1991) to support the occupancy model. In the present study, the range of numerosities has been extended to do so. Three experiments were designed to measure the effects of texture density adaptation on the perceptual dimensions of numerosity, texture density, and cluster at several numerosities, including those tested by Allik and Tuulmets. Experiment 1 compares the distortion of number and density. Experiment 2 examines the effect of texture density adaptation on the perceived numerosity and cluster of dots. Experiment 3 replicates the findings of Experiment 2, with a control for luminance adaptation and a measure of response latencies to check for different strategies of performance.

Experiment 1

The texture density aftereffect is known to affect the perception of numerosity (as well as density) when numerosity is high—more than 200 (Durgin & Proffitt, 1991). If numerosity and texture density are derived from the same process (e.g., occupancy), then we would expect both dimensions to be affected equivalently at all numerosities. On the other hand, if numerosity perception for low numerosities is based primarily on different sources of information than those relevant to perceiving density, an aftereffect of density might be expected to have little effect on perceived numerosity at those low numerosities. Although texture numerosity (beyond the subitizing range) is generally taken to be a continuous dimension, range effects within the influence of density information would be strong evidence that multiple information sources are combined in the perception of numerosity.

Experiment 1 was undertaken to quantify the effect of the texture density aftereffect on perceived numerosity and texture density across a range of numerosities. This was done to determine whether adaptation to dense texture affected perceived numerosity differently than perceived density and whether there were range-specific effects on the distortions of each dimension.

In Experiment 1, participants were adapted with dense texture in one region of the visual field and then asked to compare texture fields presented in the adapted region of their visual fields with textures in an unadapted region. One group of participants was instructed to make comparisons solely on the basis of the apparent numerosity of the texture, and a second group was instructed instead to compare the texture fields on the basis of the apparent density. To avoid ambiguity of instruction that might arise from the logical relation of numerosity and density, the participants in the density group were instructed to pay attention to the apparent spacing of the dots rather than their number. The dependent measure of the study was in both cases the ratio of the numbers of dots in the unadapted and adapted fields at the point of subjective equality (PSE).

Method

Participants

Sixteen undergraduate students at the University of Virginia received course credit for their participation.

Apparatus

The stimuli were generated and displayed on a Sun 3/60 workstation with color monitor (40 pixels/cm). The participants sat at a fixed distance (72 cm) from the screen.

Stimuli

The adaptation and test textures appeared in two $4° \times 4°$ display regions that were separated by 2° along the horizontal axis. The stimuli were similar to those shown in Figure 2. A small red square at the center of the display served as a fixation mark. The texture elements used were two-pixel square white dots subtending 0.04° of visual angle. The dots were scattered randomly against a black background except that dots were constrained not to touch or overlap. New randomized dot positions were used on each trial.

During adaptation, a series of randomized textures was displayed in each region. Each texture remained on the screen for 1 s and was then replaced by its successor. One of the regions, the adapted region, always contained 800 dots (50 dots/degree^2). Because the alternation of textures produced some apparent motion in the adaptation field, texture of low density (20 dots, approximately 1.25 dots/degree^2) was simultaneously presented in the other (unadapted) region to balance this effect. Test stimuli were displayed for 1 s and followed by a blank screen. The test numerosities presented in the dense-texture-adapted region ranged from 20 (1.25 dots/degree^2) to 320 dots (20 dots/degree^2). Participants viewed all stimuli binocularly.

Procedure

Participants were initially adapted for 3 min. The left–right position of the dense adaptation field was varied between participants. Following adaptation, participants compared simultaneously presented test fields according to one of two instruction types. Those in the numerosity condition were explicitly told to choose the field that "has the greater number of dots" and to disregard the configuration of the dots. Those individuals in the density condition were told to choose the field that "appears more dense with dots" and to disregard the absolute number of dots. In both conditions, participants were told to disregard differences in apparent dot brightness (produced by adaptation to the dense adaptation texture). Participants used the fixation mark throughout the experiment.

Individual test trials consisted of 4 s of readaptation and 1 s of blank screen followed by the presentation of test textures for 1 s. Participants indicated their choice with a keypress after the stimulus left the screen; thereafter a new set of stimuli was generated and the next test trial began. The stimuli were selected by a staircase method. The entire procedure averaged 89 trials and took approximately 25 min.

Measurement

Five staircases were used to assess the effect of density adaptation on five different numerosities presented to the adapted region of the visual field: 20, 40, 80, 160, and 320 dots (1.25–20 dots/degree^2). Each staircase was a series of trials (interleaved with trials from other staircases) in which the numerosity in the field adapted to dense texture (hereinafter, the adapted field) remained fixed, but the numerosity of the unadapted field varied by preset steps in a direction determined by the response to the previous stimulus of the staircase: If, on a given trial, a participant responded that the unadapted field was denser than the adapted field, its numerosity was decreased on a future trial. A *turn* in a staircase occurs when a response differs in direction from the response to the previous stimulus in that staircase (because this results in an increment of the unadapted field's numerosity following its decrement, or vice versa). It should be noted that the participants were unaware of the methodological distinction between the fixed (adapted) and variable (unadapted) field and were not told that their responses would affect later trials. The starting numerosity in the unadapted field for each staircase was objective equality. The initial step-size was 10% of the target value until the first turn, then 7.5% until the second turn, and 5% thereafter (except for the lowest numerosity, in which case the step size was 10%—2 dots—throughout to avoid anchoring effects produced by small step-sizes in judgments of high uncertainty). The number of dots in the unadapted field at the third through eighth turns was averaged to estimate the PSE for each staircase. To maintain synchrony between the measurements of the various staircases the random selection of a particular staircase on a given trial was weighted by the square of the turns remaining to complete that staircase.

Results

Aftereffect size, expressed as the ratio between the numbers of dots in the unadapted and the adapted fields at the PSE, is plotted by group and numerosity in Figure 5. It is evident that the aftereffect size is roughly the same at all levels of numerosity for the density group, but that the numerosity group shows a greater proportional diminution of perceived numerosity as numerosity increases. A mixed-design 2 × 5 (Group × Number) repeated measures analysis of variance (ANOVA) was performed on aftereffect size. There was a reliable between-participants difference; density judgments differed more, on average, from objective equality than numerosity judgments did, $F(1, 14) = 5.65$, $p < .05$. But more to the point, the pattern of distortions differed by group, as revealed by a marginal interaction of group and number, $F(4, 11) = 3.01$, $p = .066$. As a result, one-way repeated measures ANOVAs were done on each group separately. As anticipated, the participants who compared fields for numerosity showed a reliable effect of number, $F(4, 4) = 7.33$, $p < .05$, but the density group did not, $F(4, 4) = 1.7$, *ns*, $p > .10$.

To better understand the interaction of numerosity and group, the mean PSE for each numerosity is plotted by condition on a log-log scale in the leftmost panel of Figure 6. A slope of 1 in log space indicates a constant ratio between subjective and objective equality. The dashed line represents objective equality and has a slope of 1. Thus the constant ratio of distortion found for the density group is illustrated by a line parallel to the dashed line. To analyze the slopes of the two groups, a regression slope in log space was computed for each subject.[2] Because the distribution of slopes was skewed, a nonparametric statistic, the Wilcoxon rank sum, was used (Hollander & Wolfe, 1974). Consistent with the interaction of the prior analysis, the slopes of the density group ($M = 0.97$) and of the numerosity group ($M = 0.87$) differed reliably from each other, $T(8, 8) = 90$, $p < .01$. Signed rank statistics indicated that the slopes of the numerosity group differed reliably from 1, $T(8) = 36$, $p < .01$, whereas those of the density group did not, $T(8) = 28$, *ns*.

Discussion

The results confirm that the perception of numerosity and the perception of density are affected differently by adaptation to a dense texture. Adaptation produces a strong and consistent distortion of perceived density at all levels of numerosity. This finding is consistent with the constant ratio of distortion reported by Durgin and Proffitt (1991).

[2] Note that these slopes are effectively the exponents of the power functions relating actual to matched numerosity or density for each participant.

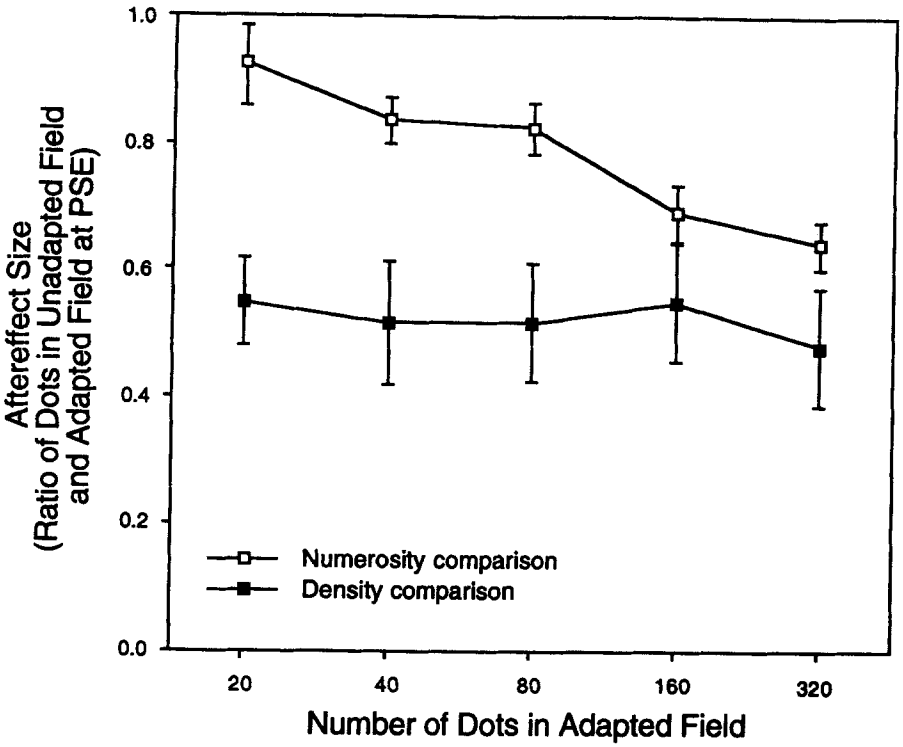


Figure 5. Experiment 1. Aftereffect size is plotted against level of numerosity for the numerosity and density groups. Aftereffect size is expressed as the ratio of matched (perceived) to actual number of dots in the adapted field at the point of subjective equality (PSE), thus an accurate match would be 1. Points plotted are geometric means.

On the other hand, the relative distortion of perceived numerosity produced by adaptation increases significantly with test numerosity,[3] as demonstrated by the analysis of slope.

Note that if the regression line of the numerosity condition passed through the origin of a log-log plot (Figure 6), then the aftereffect of numerosity could be expressed as a constant ratio of logarithms. Supposing that perceived numerosity is a logarithmic function of actual numerosity (van Oeffelen & Vos, 1982), such a result could arise if the aftereffect were a linear distortion of judged, rather than perceived, numerosity. The present data are insufficient to refute this possibility (which will be left to Experiment 2). However, it is clear that the current results of numerosity distortion cannot be interpreted in terms of logarithmic sensitivity scales: At low numerosities, the mean reduction of perceived numerosity found here for 20 dots is less than the difference limen (just noticeable difference) for that numerosity. (Allik & Tuulmets, 1991, calculated a difference limen amounting to a 15% change in numerosity for their fields of 20 dots.) The reduction of perceived numerosity for the higher numbers of dots is quite large by comparison, though the difference limen for higher numerosities is proportionally smaller (Barlow, 1978),[4] and the aftereffect exceeds it many times over.

Because density, but not numerosity, is distorted by a constant ratio, the density aftereffect resembles a linear scaling of something like apparent interdot distances rather than a direct misperception of number. The fact that numerosity distortion increases with number suggests that texture density information has an increasing influence on perceived numerosity as numerosity grows large, and that it is the distortion of density that is primary.

Experiment 2

When density is defined in terms of number, one expects distortions of perceived numerosity and density to be equiv-

[3] The conclusion that it is the numerosity rather than the density of a display that allows the dissociation between numerosity and density judgments is suggested by the findings of Durgin and Proffitt (1991), who instructed their participants to compare the fields on the basis of numerosity or density (assuming that either judgment would be mediated by perceived density). They used regions more than seven times the size of those used here that had similar densities (e.g., equivalent in density to numerosities of about 50, 100, 125, and 200 dots in the current display area) but a higher range of numerosities (350–1,500 dots). They found a constant ratio of distortion at all densities. However, their texture stimuli were composed of luminance-balanced dots and may not be comparable to the present stimuli.

[4] Currently ongoing investigations indicate that density adaptation does not affect the difference limen for density discrimination. Using the method of constant stimuli, I have found the difference limen for 320 dots, configured as in Experiment 1, to be about 7%–9% of 320 with or without adaptation.

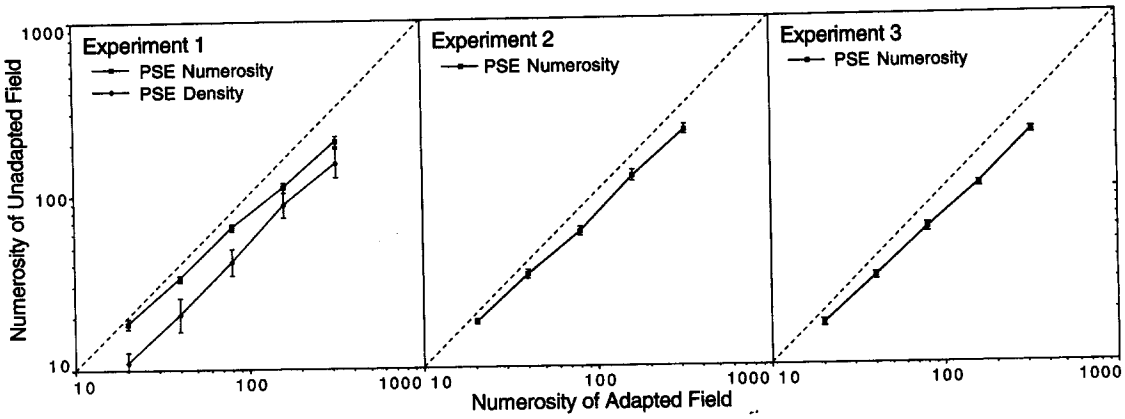


Figure 6. Results of Experiment 1 and of the numerosity phases of Experiments 2 and 3. Mean number of dots in unadapted field at the point of subjective equality (PSE) is plotted against number in the adapted field for the numerosity and density–cluster groups. Means are geometric means; error bars are based on standard errors of logarithmically transformed scores. The dashed line represents objective equality.

alent. However, we have seen in Experiment 1 that the distortions dissociate at low numerosities. It is natural to wonder what perceptual experience results from this apparent conflict. My own phenomenal impression was that the apparent cluster of dots was reduced. Ginsburg and Goldstein (1987) have suggested that the cluster coefficient of a display (a measure of density variance) is a basic feature of textures. MacKay (1964) reported that extremely steady fixation on a random texture produces a decrease both in the apparent density and in the randomness of that texture. Anstis and Ho (1992) have recently reported that adaptation to an irregular dot pattern decreases the apparent cluster (disorder) of subsequently viewed patterns.

Anstis and Ho (1992) suggested that their aftereffect of apparent cluster resulted from normalization of a perceptual dimension of disorder. To assess this possibility, Experiment 2 used a metric of dot separation that allowed the assessment of distortions of perceived cluster. The numerosity condition of Experiment 1 was first replicated with minor modifications in the first phase of Experiment 2 to assess the distortion of numerosity for each participant. In a second phase of the experiment, participants made judgments about the relative cluster of test fields at several numerosities. In this phase, the cluster rather than the numerosity of the fields was manipulated. Relative cluster was measured in two kinds of displays: The numerosity of the unadapted field was set to be either subjectively (initially) or objectively equal to the adapted field. This was done to assess whether differences in numerosity would influence the perceived relative cluster. If the distortion of the apparent cluster is due to adaptation of an independent dimension of cluster or disorder, the results should show a comparable distortion of perceived cluster at all levels of numerosity.

Method

Participants

Fifteen students at the University of Virginia were paid for their participation.

Apparatus

The stimuli were generated and displayed on a Sun 4 Sparcstation with color monitor (40 pixels/cm).

Stimuli

Display size. The stimuli for the second experiment were similar to those of Experiment 1, except that the entire display was enlarged by 20% on the screen to allow greater spatial resolution for the cluster manipulation. Participants viewed the stimuli from a proportionally greater distance (86 cm) to maintain the same visual angles.

The high-density side of the adaptation stimulus was the same as in Experiment 1 (800 dots = 50 dots/degree^2), but the low-density field was eliminated. The scatter-dot textures for the first phase were similar to those of Experiment 1. Presentation time of the test stimuli was abbreviated to 200 ms to prevent eye movements. Time of initial adaptation was reduced to 45 s, as this time seemed sufficient for the initial induction of adaptation. Intertrial readaptation was 3 s. The blank period preceding each test stimulus was 500 ms.

Dot separation manipulation. The manipulation of dot cluster was accomplished by varying the minimum interdot distance (MinID) allowed in the process that created each pseudorandom dot field. In practice this meant that a square of a given size surrounding each dot was protected against the placement of other dots during the texture generation process. For the adapting and test textures presented in the adapted field, the MinID was always three pixels, as in Experiment 1 (i.e., at least one pixel separated

each two-pixel-wide dot from every other). The MinID of a texture presented in the unadapted field was varied by altering the size of the protected region around each dot. This method easily and effectively reduces apparent cluster as the MinID is made larger. For example, the variations in apparent cluster illustrated in Figure 1 were produced by this means.

The MinID, thus defined, is a useful metric of dot cluster for the present study, because it can be scaled to the density of dots by the square root of dot density: The theoretical maximum MinID ($MinID_{max}$) for a given density would be found in a regular lattice of dots, and would therefore be a square root function of the reciprocal of dot density (i.e., $MinID_{max} = \sqrt{Area/N}$, in which N is the number of dots in the display). The ratio of the MinID to the $MinID_{max}$ is a useful expression of the cluster of displays that are generated by an otherwise random process because it expresses something about the expected variance of the dot density independent of mean density. I call this the *ratio of regularity,*[5] which can be expressed as $MinID/MinID_{max}$. When area is held constant, the ratio of regularity of two displays can be equated by setting the MinIDs such that

$$\frac{MinID_1}{MinID_2} = \frac{\sqrt{N_2}}{\sqrt{N_1}}.$$

Therefore, the MinID can be expressed either in absolute (distance) or relative (cluster) terms. In the top row of Figure 1 all the textures were generated with the same absolute MinID (3). The two lower rows were generated so that the ratio of regularity would be constant within each row. (The absolute MinIDs of the second and third rows are 4, 8, 16 and 8, 16, 32, respectively.)

It must be stressed that the ratio of regularity is not proposed as a good cluster metric for just any texture, but is useful only for manipulating cluster in the texture generation process (random scatter) used here.

Procedure

Each participant was tested in the two phases of the experiment in succession, first for perceived numerosity, then for perceived cluster. The instructions for the first phase explicitly indicated that numerosity alone was to be judged and that differences in apparent brightness, size, or distribution of dots should be disregarded. The instructions for the second phase were to choose the more clustered of the two fields, ignoring number and all other extraneous dimensions. Participants were shown examples of textures with differences in cluster at several numerosities to familiarize them with the dimension to be judged. The instructions for both phases were given in advance of the first phase.

After the initial adaptation period, participants were assessed for numerosity perception as in Experiment 1. Participants made forced-choice comparisons of simultaneously presented texture fields. Apart from shorter presentation times the stimuli were defined like those of Experiment 1 and were measured in the same way, with readaptation between each judgment. At the end of this phase, the participant pressed a button to go on to the cluster judgment phase, which proceeded in similar fashion, except that the number of dots in the two fields was kept constant and the MinID was varied. The first phase averaged 84 trials and the second phase, 112. Because of the more rapid generation and presentation of stimuli made possible by the faster computer, the entire testing procedure still averaged 25 min.

Measurement

Phase 1: Numerosity. The stimuli of the first phase were defined like those of Experiment 1 and measured in the same way. That is, the same five numerosities (20, 40, 80, 160, and 320) were used in five interleaved staircases with step sizes identical to those of Experiment 1.

Phase 2: Cluster. The measurement of perceived cluster was undertaken for numerosities of 20, 80, and 320 dots presented in the adapted region with a MinID of three pixels. For each level of numerosity two values of apparent cluster were gathered: one with objectively the same number of dots in the unadapted field (objective equality, or OE) and one with the PSE from the first phase in the unadapted field. Thus there were six staircases interleaved in the second phase.

The MinID of the unadapted field started at three for each staircase (OE) and then changed by decreasing step-sizes until reaching the second turn, at which the final step-size was one pixel for the high-numerosity fields, two pixels for the medium-numerosity fields, and three pixels for the lowest numerosities. To ensure that locations would be found for all the dots, an upper bound was set on the MinID for each staircase (60% of the $MinID_{max}$). A lower bound of two pixels prevented dots from overlapping. For some participants floor or ceiling effects were evident in the high-numerosity stimuli because of these limitations. The score in these cases was set at the extreme if more than 60% of their responses to the extreme stimuli indicated that a value beyond the extreme was required. Because floor and ceiling effects can artificially reduce variance, leading to a false rejection of the null hypothesis, these effects will be discussed in the *Results* section.

The MinID scores obtained in this way can be analyzed in either of two ways. They can be taken as raw distortions of minimum interdot distance (absolute MinID) or adjusted to represent the relative difference in cluster between the adapted and unadapted fields at the PSE. To make the MinIDs of the OE and PSE stimuli comparable in relative terms, the MinIDs of the PSE stimuli were multiplied by the square root of the ratio of the numbers of dots in the unadapted and adapted fields (adjusted MinID). The logarithms of these adjusted scores were used for statistical analysis of the distortion of cluster because an arithmetic difference in log space is equivalent to a ratio in untransformed space. Because the MinIDs of the adapted fields were constant, a log-transformed adjusted score serves as a measure of the difference in relative cluster between the adapted and unadapted fields.

[5] I refer to the ratio of the MinID and the $MinID_{max}$ as the *ratio of regularity* rather than "cluster ratio" because it is not a direct measure of the variance of density and it can only be applied to the continuum of textures from regular (lattice) to random scatter, whereas the variance of texture density can be increased beyond that of a random texture (but not by the manipulation of the MinID). Although cluster and regularity are not precisely reciprocal concepts (a periodic regular pattern can be made up of clumps of dots and thus have a high variance of density), manipulation of the MinID allowed in the algorithm that generates a pseudorandom dot field does affect them in a qualitatively reciprocal fashion. Note that other means of altering the MinID of a texture, such as moving one dot close to another in an otherwise unclustered display, would violate the assumptions underlying the use of the MinID to manipulate cluster in the present study.

Results

Numerosity

The results of the first phase of the experiment are plotted in the center panel of Figure 6. The pattern of results replicates the findings from the numerosity condition of Experiment 1. In log space the mean slope (M = 0.91) of these participants is reliably less than 1, $T(15) = 97$, $p < .05$.

It might be argued that a judgmental illusion of numerosity should be represented as the ratio of the logarithms of numbers of dots. To test whether the present distortion of numerosity could be expressed as a constant ratio of logarithms, the data from the numerosity group of Experiment 1 were combined with the numerosity data from Experiment 2 for analysis. Individual slopes were computed for each participant from the ratios of the logarithms over the logarithm of numerosity. These slopes (M = −0.012) were reliably different from 0, indicating that even expressed as a ratio of logarithms the distortion of numerosity increases with numerosity, $t(22) = 2.51$, $p < .05$.

Cluster

The mean values of the absolute and adjusted MinIDs at the PSE for cluster are shown in the leftmost panel of Figure 7. Because nearly a third of the scores in each of the high-numerosity conditions were affected by the floor of 2 that was placed on the MinID, the high-numerosity scores were analyzed separately from the rest of the data. The absolute MinIDs of the high-numerosity stimuli have their medians at 3.33 (numerosity at PSE of Phase 1) and 2.83 (numerosity at OE). Despite the artificially reduced variability produced by the floor effects in these measures, neither differs reliably from 3 in the mean absolute MinID, M(PSE) = 3.69, $t(14) = 1.39$, *ns*, and M(OE) = 3.59, $t(14) = 1.18$, *ns*. Nor do the log-transformed, adjusted MinIDs differ from log(3), M(PSE) = log(2.78), $t(14) = 0.60$, *ns*, and M(OE) = log(3.20), $t(14) = 0.52$, *ns*. That is, there is no evidence of consistent distortion of the absolute MinID or of the relative cluster of the 320-dot fields.

On the other hand, the MinIDs for the 20- and 80-dot groups are clearly much higher than 3. For example, even for the 80-dot/PSE stimuli, which show the least distortion, the logarithm of the adjusted MinID differs reliably from log(3), M(PSE) = log(5.0), $t(14) = 3.67$, $p < .01$.

A 2 × 2 (Relative Numerosity of Unadapted Field: PSE or OE × Numerosity: 20 or 80) repeated measures ANOVA was performed on the logarithm of the adjusted MinIDs (excluding the 320-dot data). There was a reliable effect of numerosity, $F(1, 14) = 63.8$, $p < .0001$, indicating that there was greater distortion of cluster for the 20-dot than for the 80-dot textures. There was also a marginal effect of the PSE–OE factor, $F(1, 14) = 4.45$, $p = .053$, suggesting that the cluster of the unadapted field required more distortion when the numerosities of the two fields were objectively equivalent.

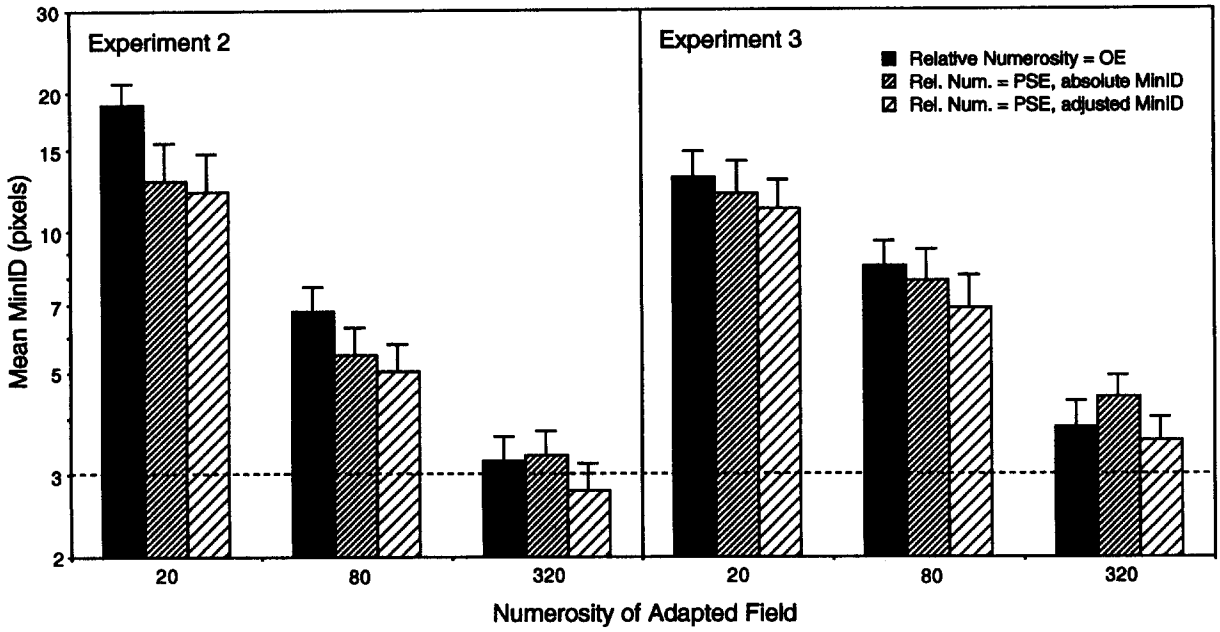


Figure 7. Results of cluster phase of Experiments 2 and 3. The mean values of the absolute objective equality (OE) and point of subjective equality (PSE) and adjusted (PSE only) minimum interdot distances (MinIDs) of the unadapted field at the PSE for cluster are plotted against numerosity of the texture in the adapted field. Means (geometric) and standard errors are derived from logarithmically transformed scores. The dashed line represents the MinID of the standard fields.

To illustrate the effect of the relative numerosity of the unadapted field, Figure 8 shows median ratios of regularity ($MinID/MinID_{max}$) plotted against numerosity of the adapted field. The difference between the PSE and the OE data might reflect an interaction between numerosity and perceived cluster, which is particularly evident for the textures compared with the 80-dot adapted-field textures.

Discussion

The results of the numerosity phase are consistent with the results of Experiment 1. Despite the linear distortion of density produced by the density aftereffect, adaptation to dense texture produces a greater distortion of numerosity at higher numerosities than at lower numerosities whether that distortion is measured as a simple ratio or as a ratio of logarithmically transformed values. It seems that the distortion of density information is less influential in the perception of numerosity when numerosity is low.

The opposite pattern of results is found for perceived cluster: There is no evidence of a systematic distortion of perceived cluster at the highest numerosity used, but in the range of numbers within which perceived numerosity is least affected by adaptation, the greatest distortion of perceived cluster occurs. This range-dependent effect cannot be explained by the adaptation of disorder per se.

Indeed, the fact that the distortion of cluster is complementary to the distortion of numerosity may not be accidental. I have suggested that a distortion of cluster might arise as a consequence of a conflict between perceived density and perceived numerosity. I will first consider an alternative explanation.

An adaptation of high densities (small interdot distances) might well influence the effective relative presence of various interdot distances in a texture. The reduction of cluster shown in the lower panels of Figure 1 is produced by an actual attenuation of high densities. A subjective attenuation of high densities produced by adaptation could produce the same effect if cluster were simply computed from the variance of densities apparently present.

However, the large change of the MinID required for the 20-dot fields vastly exceeds the distortion of density measured in Experiment 1: A distortion of density by a factor of 2 represents a linear distortion of distance by the square root of 2; the mean linear distortion of the MinID found for the 20-dot fields is by a factor of 4. In addition, no differential distortion is found for the 320-dot fields, although, as the reader may observe from the textures of Figure 2, an 800-dot adapting texture (Panel A) appears substantially higher in density than a 320-dot texture (Panel B). Finally, the results indicate that judgments of relative cluster are affected by the relative numerosity of the textures to be compared. This fact and the reciprocal relation between distortions of numerosity and cluster suggest that the distortion of cluster should not be considered in isolation from perceived numerosity.

In general the reciprocal effects of adaptation on numerosity and cluster suggest that distortions of these two dimensions may actually trade off. We have seen in Experiment 1 that density judgments and numerosity judgments conflict at low numerosities. It is possible that the distortion of perceived cluster may come about as a perceptual resolution of this conflict. Such a resolution is sensible because, as shown in Figure 1, a spreading apart of dots (reduction in

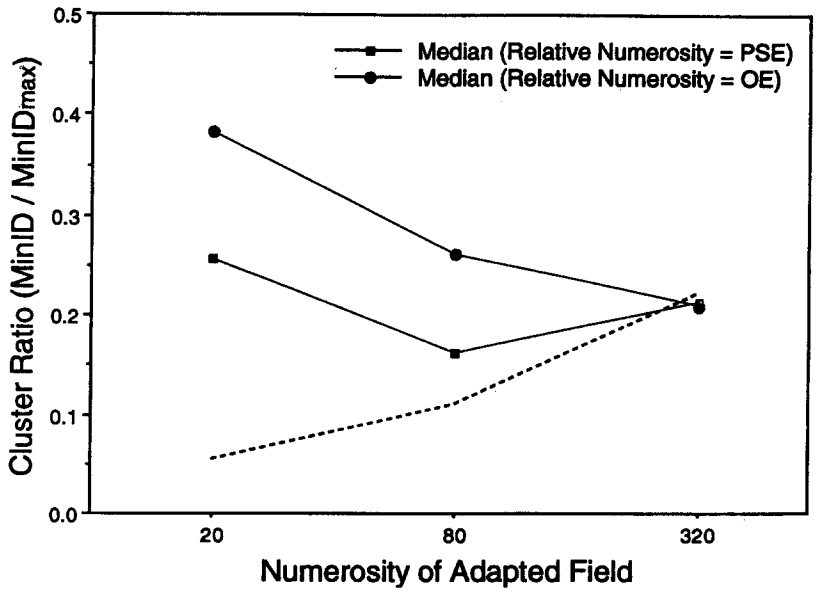


Figure 8. Cluster phase of Experiment 2. Median ratios of regularity ($MinID/MinID_{max}$) are plotted for three levels of numerosity under conditions in which the relative number of dots in the unadapted field was subjectively equal (PSE) or objectively equal (OE). The dashed line represents the ratio of regularity of the adapted field.

local density) without a concomitant reduction in apparent numerosity is consistent with a texture that is reduced in cluster.

Experiment 3

Although prior research on the density aftereffect has suggested that luminance is not an essential factor (Durgin & Proffitt, 1991), there is evidence of perceptual interactions between perceived brightness and perceived density (Mulligan & MacLeod, 1988). Because the methods used in Experiments 1 and 2 did not control for possible effects of luminance adaptation, a third experiment, replicating the results of Experiment 2, was performed in which the luminance of the dense adapting texture was matched with a homogeneous gray square presented in the other region during adaptation.

In addition, decision latencies were recorded and analyzed in Experiment 3. The range-dependent effects of numerosity of the previous experiments might suggest that a radically different strategy (e.g., grouping and adding) is responsible for the more accurate comparisons in the lower ranges. If the nondistortion of the lower numerosities were due to information from a serial group-and-add process, longer reaction times would be expected for those judgments. On the other hand, if the comparisons of the lower numerosities are accomplished by a parallel analysis of spatial information (e.g., the occupancy index of Allik & Tuulmets, 1991), then there is little reason to expect different response latencies for the different numerosities.

Method

Participants

Sixteen undergraduate students at the University of Virginia received course credit for their participation.

Apparatus and Stimuli

The apparatus and stimuli were identical to those used in Experiment 2 except that a homogeneous square of the same average luminance as the adapting texture (2.6 cd/m^2) was presented in the non-density-adapted region during adaptation and readaptation.

Procedure and Measurement

The procedure was also the same as in Experiment 2, except that response latencies (time between onset of stimulus and response) were recorded for analysis. As before, instructions to subjects emphasized accuracy rather than speed of response. However, the short duration of the test stimuli encourages rapid performance.

The analysis of participants' response latencies in their numerosity comparisons was performed on the median reaction time (RT) of each participant at each numerosity. To minimize differences produced by difficulty of discrimination or novelty of the task, only the RTs for trials after the second turn in each measurement staircase were used (the same trials from which the PSEs are calculated).

Results

Numerosity

The numerosity comparison results of the first phase of the experiment are plotted in the rightmost panel of Figure 6. The pattern of results replicates the findings from the numerosity conditions of Experiments 1 and 2. A within-participants repeated measures ANOVA on the log of the ratio of dots in the unadapted and adapted fields revealed a highly reliable main effect of numerosity, $F(4, 12) = 12.45$, $p < .01$. In log space the mean slope ($M = 0.90$) of these participants is reliably less than 1, $T(16) = 135$, $p < .01$.

Apart from a single participant who demonstrated a median RT of more than 2,700 ms in the 20-dot comparisons, median latencies ($M = 1193$ ms) do not suggest that participants' judgments entail counting. Such a process typically involves 60–200 ms per item and would be further complicated because two briefly presented fields must be assessed on each trial. A within-participants repeated measures ANOVA revealed no effect of numerosity on median response latency, $F(4, 12) = 2.10$, *ns*, nor was there any correlation between response latency and aftereffect size in the 20-dot condition, $r = .06$, *ns*.

Cluster

The results of the second phase of the experiment are plotted in the rightmost panel of Figure 7. The pattern of results replicates the main finding of the cluster phase of Experiment 2. There is pronounced distortion of cluster for the low-numerosity displays. As in Experiment 2, it was necessary to analyze the results of the high-numerosity condition separately because of the skewed distribution of results produced by floor effects. The data illustrated in the right panel of Figure 7 might seem to suggest there is some distortion of cluster even for the highest numerosity displays, but this may be partly a result of the skewed distribution of responses. The absolute MinIDs of the high-numerosity stimuli have their medians at 3.59 (numerosity at PSE of Phase 1) and 3.25 (numerosity at OE). In fact, the mean absolute MinID does differ reliably from 3 in the PSE condition, $M(\text{PSE}) = 4.39$, $t(15) = 2.17$, $p < .01$, but not in the OE condition, $M(\text{OE}) = 3.77$, $t(15) = 1.63$, *ns*. Moreover, when the MinID scores in the PSE condition are adjusted relative to the number of dots present in the unadapted field (median = 3.1), the results do not differ from 3, $M(\text{PSE, adjusted}) = 3.56$, $t(15) = 1.40$, *ns*. Thus, there is no evidence of distortion of cluster for the 320-dot fields, despite the elevation of the means that is evident in the figure.

As in Experiment 2, the MinIDs for the 20- and 80-dot fields are clearly much higher than 3. A 2 × 2 (Relative Numerosity of Unadapted Field: PSE or OE × Numerosity: 20 or 80) repeated measures ANOVA was performed on the logarithm of the adjusted MinIDs (excluding the 320-dot data). There was a reliable effect of numerosity, $F(1, 15) = 5.55$, $p < .05$, indicating that there was greater distortion of cluster for the 20-dot than for the 80-dot textures. There

was no effect of the PSE–OE factor, $F(1, 15) = 1.22$, *ns*, although the pattern is in the same direction as in Experiment 2.

Discussion

Overall, the results of both the numerosity and cluster phases replicate the findings of Experiment 2 and support the interpretation offered. The latency data offer convergent evidence that the judgments in all cases are based on assessments of spatial aspects of the display that are processed in parallel, rather than on a serial counting mechanism. The matching of luminance between the dense-adapted and unadapted regions during adaptation did not change the character of the results. As before, the distortions of cluster and numerosity are strong, range dependent, and complementary.

These results suggest that distortions of cluster and numerosity represent complementary perceptual accommodations reflecting the integration of distorted density information with other, undistorted sources of information concerning those dimensions.

General Discussion

Naturally occurring and manmade surfaces are commonly patterned with irregular textures. In the three experiments reported here I have examined some salient dimensions along which the spatial properties of such textures can be discriminated. By examining the effects of adapting to dense texture upon the perception of each of these dimensions, I have sought to elucidate how the perceptual representation of each of these dimensions might be constrained by the conceptual and perceptual relations between them.

The specific dimensions studied in this article were the perceived numerosity, cluster, and density of texture. I have shown that texture density adaptation has qualitatively different perceptual consequences at different levels of numerosity. These qualitative differences have been demonstrated by showing that the quantitative effects of density adaptation on perceived cluster and perceived numerosity vary with the level of numerosity in complementary ways.

I will now discuss the implications of this research for understanding the perception of numerosity and then turn to a brief discussion of texture density.

Perceived Numerosity

Although prior psychophysical studies have discovered no discontinuity in functions of perceived numerosity beyond the subitizing range (Indow & Ida, 1977; Kaufman et al., 1949; Krueger, 1972; Taves, 1941), it is probable that the visual discrimination of numerosity is based on a number of cues that are differentially useful at various ranges of numerosity or density. Indeed, the current results almost necessitate such a conclusion, for it is clear that perceived numerosity is affected by density adaptation differently depending on the range of numerosity in question. Consistent with Barlow's (1978) subjective distinctions between judgments based on numerosity and dot density, these two perceptual dimensions (numerosity and texture density) are empirically separable.

How might an occupancy model be modified to fit the findings of this article? Allik and Tuulmets (1991) intended their model to be applied to all levels of numerosity, and have demonstrated that the effect of cluster on numerosity (which the occupancy model was designed to explain) exists for numerosity values as high as 1,500 dots. However, they have found an empirical value of the occupancy radius (R) that is inadequate for the task of discriminating dense textures. If the value of the occupancy radius is variable, as Allik and Tuulmets (1991; Allik, Tuulmets, & Vos, 1991) suggested, then there might be two quantities that specify the numerosity of a field: (a) the occupancy index, with its implicit occupancy radius, R, and (b) a value of R (R') used to interpret that index. For example, if I measure the occupied area of a dot field using a blob size that can vary, I must take the blob size into account. A simple way to do this would be to divide the occupancy index (total area) by the area of the blob (πR^2). The parameter used to interpret the occupancy index need not be identical to that used to derive the index, which is why I have called it R'. At a first pass it would appear that the occupancy index and R' might correspond roughly to area and density, respectively, which are sensible factors for the estimation of number. If we assume that it is R' that is affected by adaptation to dense texture, a differential weighting of occupancy and density information at different levels of numerosity may still be required to explain the effects of density adaptation on numerosity discrimination.

But what if adaptation affected the selection of R itself? This could be the case if density information were used in the selection of the R value applied to a given texture. For the sake of argument, suppose that the measured distortions in density reflect the quantitative distortion of R. In other words, because density is misperceived by approximately a factor of 2, let us assume that πR^2 is being inflated by a factor of 2 and that the linear value of R is therefore being inflated by the square root of 2. If numerosity is computed by dividing the occupancy index found by πR^2, then for an already filled texture this would have the consequence of reducing perceived numerosity by a factor of nearly 2,[6] but for an unfilled region, the distortion of R would result in somewhat less distortion of perceived numerosity. For example, in the limit, a 1-dot field would be completely unaffected inasmuch as the occupancy index of such a field would always be πR^2. The expected distortion should therefore go from none to a factor of 2 as numerosity increases. At a qualitative level, this seems to be a fair description of

[6] The distortion of numerosity might still be somewhat less than that of density itself, because the outer bounds of the occupied region, and therefore its total effective area, would be expanded slightly by the change in R.

the data: There is little distortion for low numerosities, and distortion increases with numerosity. Admittedly, if the R value computed by Allik and Tuulmets (1991) is always assumed for the unadapted field, then this should predict that the distortion of numerosity should begin to asymptote at the point at which the texture fields become essentially full. However, by our current hypothesis, R is modulated by density to begin with so that there is no reason to expect that distortion will actually reach an asymptote in the range of values tested.

A Simulation of Occupancy

To better understand the psychophysical properties predicted by the occupancy model, I have run a simulation of the model trying several values for R that bracket the value found by Allik and Tuulmets (1991) using texture fields of the same dimensions. For each preselected value of R, and for each of the numerosities used in the experiments reported above, I fed the model 100 randomly generated samples of textures like those used in the experiments (MinID = 3). For the output of my simulation I divided the occupancy index (filled area) of each texture by πR^2 (the occupancy index itself would obviously be artifactually sensitive to the choice of R). The results of the simulation are shown in Figure 9.

The simulation is very instructive. First of all, the breakdown of the occupancy model at high densities is illustrated by the decelerating slopes of the lower curves. With an R of 20′, for example, 160 dots and 320 dots have numerosity values (proportional occupancy measures) of 50 and 55, respectively, whereas those of 20 and 40 dots have values of 17 and 28, respectively. Because the Weber fraction for numerosity does not increase with numerosity, this decrease in sensitivity is not a desirable property for a model of numerosity perception. Although the units used here may be considered arbitrary (despite being chosen nonarbitrarily), the scale for each individual curve is not entirely arbitrary. Because the curves are plotted in log-log space, a power function, which is the typical psychophysical function found for numerosity perception (e.g., Krueger, 1984), would appear as a straight line. Short of reducing R to a value very close to the radius of the texture elements themselves (as suggested by the case in which R = 4′), the simplest way of obtaining a straight line from an occupancy model is to have R vary systematically with density.

The occupancy model was developed to account for the effect of varying the spatial distribution of dots on perceived numerosity, and Allik, Helsper, and Vos (1991) have reported that cluster effects are present for all numerosity values they tested—up to 1,500 dots. To demonstrate the effect of varying the cluster of the textures on the model, I ran the simulation again and manipulated the ratio of regularity of the textures. (In this case I used textures that

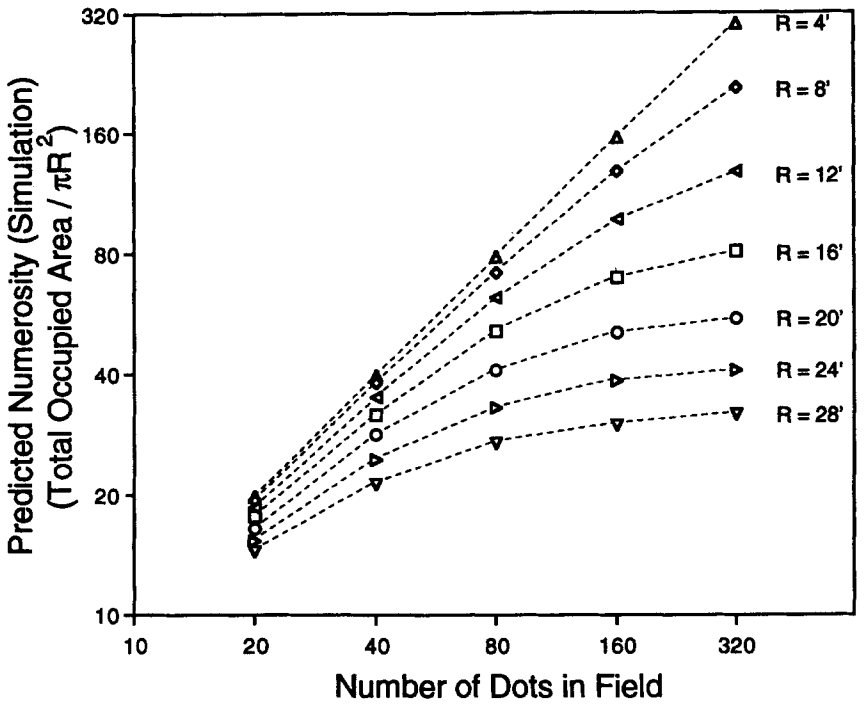


Figure 9. Data from simulation of occupancy model for several values of the radius of occupancy, R. For this range of numerosities, the output of the model will approach a power function (linear growth in log-log space) only as the value of R approaches the radius of the individual texture elements. Each mean is computed from 100 samples. The standard error of the mean is smaller than the plot symbols.

maintained one of two values of the ratio of regularity, which means that the MinIDs varied between numerosities, as was illustrated in Figure 1.) The results of this simulation are shown in Figure 10. If the model were to fit the empirical findings, it should demonstrate large changes of occupancy (perceived numerosity) produced by changes in the distribution of texture elements, such as doubling the ratio of regularity, as was done here. However, it is again clear from inspection of the data that an occupancy model can only reproduce the effect of the spatial distribution of elements if different R values are used for different densities of dots: When R is set at 20′ (the value originally specified by Allik & Tuulmets, 1991), spatial distribution does not affect the derived occupancy of 320 dots, but does so for 20 and 40 dots. Conversely, when R is set to 5′, for example, the model no longer produces differences for low numerosities, but demonstrates the expected effects at high numerosities, at which more regular textures now have higher occupancy values. It is clear from the simulation that the predicted effect of a given change in regularity is a function both of density and of R.

The possibility clearly suggested by both of these simulations is that for an occupancy model to fit the psychophysical data, R must vary with texture density, and this means that density information must be presupposed by the model. In fact, the simplest assumption would be that it varies as the square root of density, for this would accomplish size scaling between textures automatically. However, a straight line fit to points generated with this assumption in Figure 9 is a power function with an exponent of 1.00 (i.e., a linear fit). Lower exponents (about .85) are typically reported for numerosity judgments (although see Masin, 1983, for a summary and critique), so it may be that R does not scale perfectly with objective density. It would be interesting to determine whether dot radius (which would seem to place a lower bound on R) affects the scaling of numerosity against density.

Although it may seem a sensible modification of the model, the systematic variation of R with density poses a problem for the original occupancy model: Allik, Tuulmets, and Vos (1991) suggested that R could vary with the magnification of the size of a dot field and interpreted this within the context of size scaling. However, the present analysis indicates that it should vary with density even in the absence of overall size changes. But if R can vary, why does the system not use the smallest R available in all cases to reduce overall errors? Further investigation is clearly warranted to try to specify what determines R in a given situation. At present it would seem to be a correlate of density.

One very interesting possibility for the specification of R is suggested by the data from the second simulation: The R

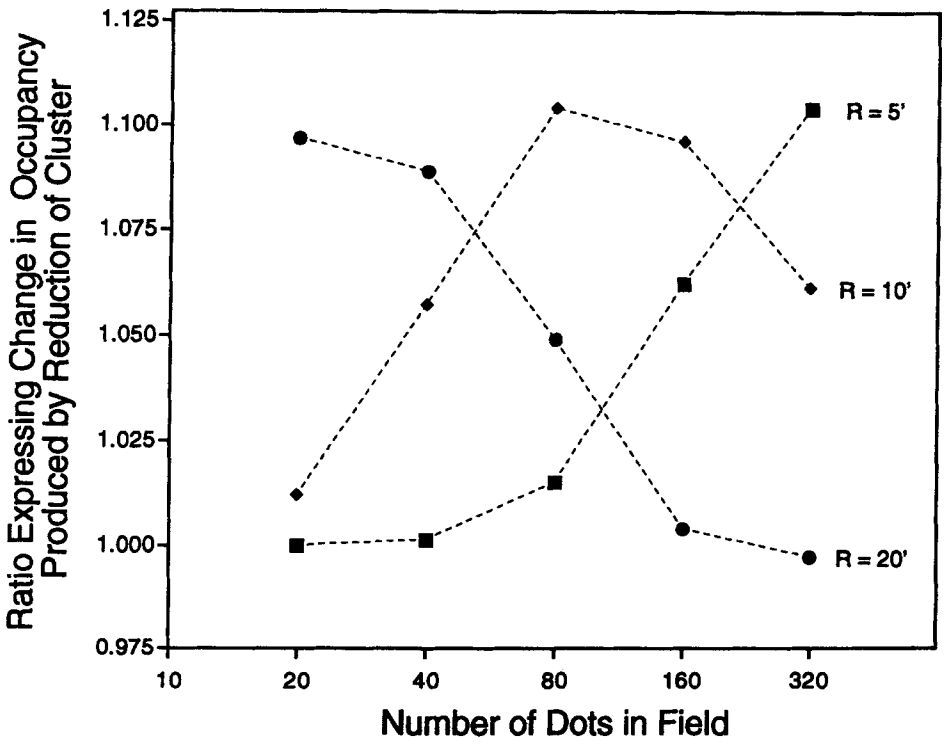


Figure 10. Data from simulation of occupancy model. Occupancy was computed for 100 textures generated at each of five numerosities with ratios of regularity set to 0.22 and 0.45. Ratio of occupancy values between the two levels of regularity are plotted against number of dots for several values of R. Occupancy index is affected by changes in cluster for only a range of values of R that varies systematically with density.

empirically derived by Allik & Tuulmets (1991) is, coincidentally, very close to the value in the simulation that maximizes the effect of cluster on perceived numerosity. By varying R more finely and looking at a wide range of cluster values, I have observed that the R that maximizes the effect of cluster for 20 dots is about 22′–25′,[7] whereas that for 40 dots is about 15′–18′. These two values bracket the mean best-fit value of R (20′) determined empirically by Allik and Tuulmets when they used fields of 20 and 40 dots. In other words, using one additional assumption (that the R that maximizes the effect of cluster on numerosity for a given density is used), it appears it may be possible to remove all free parameters from the model. However, if this revision of the occupancy model is correct, then the visual system is choosing a spatial scale of analysis that maximizes errors in perceiving numerosity. Why should it do that? A plausible explanation is that this value represents the spatial scale at which the cluster of a texture can be best represented, and thus that R is not chosen primarily for the sake of numerosity discrimination but rather for the sake of cluster or variance-of-density discrimination. If this is true, then the cognitive task of discriminating numerosity may be dependent on a visual system that is more concerned with extracting useful identifying characteristics of textures, such as their characteristic spatial distribution.

Finally, although the simulation data suggest that the occupancy model is in need of revision, and although it appears that it is currently too underconstrained for precise quantitative analysis of the effects of density adaptation (on R, for example), some qualitative observations can be made. For example, the simulation data shown in Figure 9 indicate that any perceptual distortions affecting R would be likely to produce a greater proportional distortion of perceived numerosity as numerosity increases. This can be deduced from the greater distances between the curves produced by different values of R at higher levels of numerosity.[8] In this sense, the simulation may be said to support the idea that a modified version of the occupancy model might be able to account for the finding that density adaptation (a shift in R) seems to produce range-dependent effects on perceived numerosity. This is an important feature of the simulation that should not be overlooked. Although the pattern of adaptation data is consistent with an occupancy model in this sense, it can hardly be said to be supportive of the model as previously formulated (numerosity = occupied area). However, because a simple description of the state of affairs expressed by the simulation is that the influence of density (i.e., the choice of R) on numerosity judgments increases with increased density, it appears that the proposed modification of the occupancy model to include a representation of density may be sufficient to account for the empirically different patterns of distortions of numerosity and density described above.

Numerosity: One or Many?

Although it has been shown that in normal circumstances numerosity perception appears to be independent of variations in density (Allik, Tuulmets, & Vos, 1991; Burgess & Barlow, 1983; Krueger, 1972), the present findings indicate that the influence of density adaptation (and presumably density information) on numerosity perception is not independent of the level of numerosity. For the range of numerosities tested by Allik and Tuulmets (1991), the occupancy index (filled area) of the displays was evidently a primary determinant of numerosity decisions and, as the simulations demonstrate, the choice of R is fairly inconsequential in this range with respect to numerosity. The minimal effect of texture density adaptation on the perception of these low numerosities seems to confirm that the practical contribution of density information in this range is slight. On the other hand, the comparison of higher numerosities is strongly affected by texture density adaptation. Although something like occupied area probably remains important at high numerosities (Allik, Helsper, & Vos, 1991), it appears that density information has a substantial influence on the perceptual evaluation of numerosity in high-numerosity displays. I conclude that perceived numerosity is related to actual number by means of (at least) these two intermediate kinds of visually available information and probably by their interaction.

This conclusion may appear surprising given the apparent successes of the modification of the occupancy model that I have proposed: If R is variable then the occupancy model can explain both density and area effects in one simple formula. It is important to note, however, that the reason the modified occupancy model succeeds in modeling the current data is that for high numerosities (with the same cluster values), the area into which the dots are cast becomes full, such that the model must discriminate higher numerosities using primarily density information (spatial scale). In other words, the model is successful because area information and density information have different effective weightings at different levels of numerosity.

Much of the controversy surrounding the nature of our perceptual sensitivity to numerosity has focused on the subitizing range. Although the subitizing range was not tested in these experiments, there are some theoretical implications that deserve comment. For example, Gallistel and Gelman (1992) proposed that subitizing is analogous to preverbal counting that has been studied in rats (Meck & Church, 1983), but that the assessment of somewhat higher numerosities may involve very rapid (verbal) counting. Certainly, the means by which a numerosity decision is determined for a field of dots is task dependent; given time, motivation, and perhaps some help in keeping track of which elements have already been counted (such as serial

[7] It is also evident from the simulation that the peak effect of cluster seems to vary regularly with the level of cluster. This fact, too, may need to be taken into account in revising the occupancy model. However, the particular method of regularizing textures that I have used may contribute artifacts to the fine details of the simulation, so I have not sought to further quantify this aspect of the data at present.

[8] In log space, equal proportions are expressed by equal distances.

presentation of elements in time, as in the work of Meck and Church), participants could always count dots. However, rapid simultaneous presentation, effects of spatial distribution, and the limits of short-term memory (Miller, 1956) indicate that the visual estimation of numerosity past 20 elements does not involve one-to-one mapping of texture elements to preverbal counting units. My findings support the notion that the assessment of number can be accomplished from a variety of cues, many of which do not resemble counting.

Recent evidence of stored numerical representations in infants supports the general notion that number is a meaningful conceptual dimension from very early on (Starkey & Cooper, 1980; Wynn, 1992). However, the controversy over whether subitizing involves a specialized encoding strategy may underestimate the power of the visual system as an efficient interface that can exploit a variety of kinds of information to derive values along an abstract dimension such as numerosity. The findings of Allik and Tuulmets (1991), combined with the range-dependent influences of texture density found in this article, suggest that there are many kinds of visually available information by which the perceptual evaluation of numerosity is accomplished when counting is not involved. Furthermore, the analysis presented of the occupancy model simulation suggests that the visual system may be more interested in other properties of textures (e.g., spatial pattern and regularity) than their numerosity. However, the perceptual system's apparent resourcefulness in representing numerosity is consistent with what might be expected of a system representing an abstract dimension.

Texture Density and Distribution

We have seen that the adaptation to dense texture actually produces a variety of perceptual aftereffects. Because the dimension of density itself appears to be consistently affected at all levels of numerosity, I have argued that it is this dimension that is primarily distorted by adaptation, and that the other effects are derivative. This interpretation suggests that texture density has a kind of primacy in the perceptual processing and representation of texture, but the role of the variance of texture has been underscored as well. In representing a texture, such as the leaves on a tree, the extent of the texture sample is irrelevant; therefore, such judgments ought not to be based on the numerosity of the texture but rather on density. On the other hand, variance of density may be an even more useful attribute of texture because it survives size scaling produced by different viewing distances. The dimension of cluster may be defined as the variance of the statistical distribution of interdot distances present in a texture. Although cluster is a perceptually distinct attribute of texture (participants found the judgment of relative cluster conceptually straightforward), the representation of cluster may derive from a variety of information sources including the variance of densities apparent in a texture. Thus, it is arguable that texture distribution is typically a far more meaningful property of visual textures than is numerosity per se (e.g., for coding and recognition of surface properties specific to substances and materials). Moreover, there is some suggestion from the simulation data that cluster and density may play defining roles in the visual representation of texture from which numerosity information is extracted.

In summary, the relationships among the perceptual dimensions of numerosity, density, and cluster must be determined empirically. It is theoretically possible to derive density from numerosity and area and, conversely, it is probably possible to derive something like cluster without density information. However, the current data suggest that the visual system represents texture density independent of number, and that the representation of perceived cluster depends in part on the processes underlying the perception of texture density.

Like the spatial frequency aftereffect (Blakemore & Sutton, 1969), the texture density aftereffect is the distortion of an abstract dimension (apparent dot frequency or interdot spacing). In a traditional spatial frequency aftereffect, size perception is abstracted from location of edges. The density aftereffect can also be construed as a size effect in which dots appear more spread out from one another. Indeed, the similarity between the present findings and spatial frequency adaptation might suggest that they derive from the same mechanisms. However, adaptation to scatter-dot patterns does not produce any spatial frequency-specific loss of contrast sensitivity unless individual dots are paired at a constant distance and orientation (De Valois & Switkes, 1980), suggesting that aftereffects of density and spatial frequency do not rely on the same mechanism. Moreover, interocular transfer of the density aftereffect can be blocked by patching the unadapted eye during adaptation (Durgin, 1992), whereas size aftereffects associated with spatial frequency adaptation show complete interocular transfer (e.g., Meyer, 1974).

Gibson (1950) argued that texture density was an important variable in the perception of surface orientation. Illustrations of pebbled beaches and other receding textures have long served as evidence of the supposed importance of a gradient of texture density. However, in these illustrations, gradients of density are confounded with gradients of element size or perspective as shown in Panel A of Figure 11. When element size is held constant, gradients of density produce little or no impression of depth (Cutting & Millard, 1984; Stevens, 1981). Thus, although texture provides information about depth, it appears that a gradient of density presented in isolation is interpreted as an intrinsic property of the texture, rather than of its orientation in depth, as illustrated in Panel C of Figure 11. The importance of the variance of texture distribution is illustrated by the comparison of Panels B and C of Figure 11. In Panel B, the ratio of regularity is maintained across the texture. As a result, the texture is more consistent with a sloped surface than that of Panel C. The failure to recover depth information from texture density alone may be due to a conflict with cues of texture size or distribution.

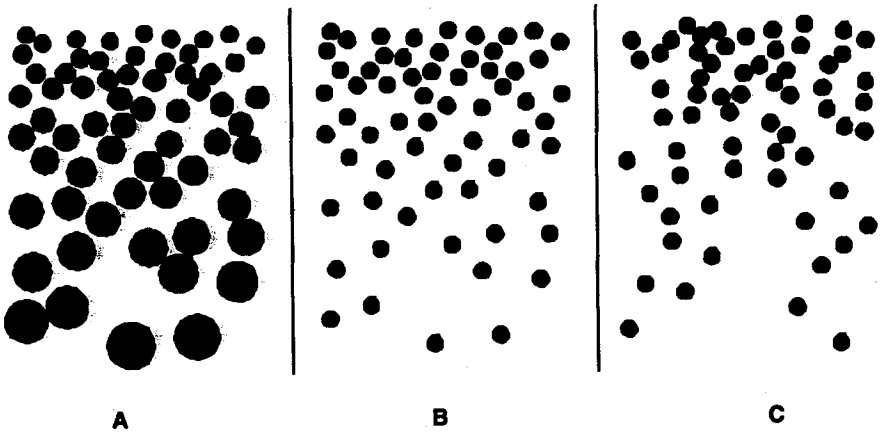


Figure 11. A receding texture varies in density and in size (panel A). A gradient of texture density isolated from the texture size gradient (panel B) does not produce a strong impression of depth (after Stevens, 1981). In panel C, density varies as in B, but the ratio of regularity is not maintained. The texture is less compelling as a surface, and all sense of depth is lost.

Conclusion

Allik and Tuulmets (1991) pointed out that the relationship between a stimulus attribute (e.g., number of dots) and its perceptual representation (perceived numerosity) need not reflect a process that is sensitive to the stimulus attribute directly. In their case the perception of numerosity seemed to be determined by a measure of area. Their theoretical point is reinforced by the current findings, although the specifics of their model are challenged. At present it seems likely that numerosity perception is based on multiple kinds of information, and a modification of the occupancy model has been suggested that integrates into it density information and, indirectly, cluster information.

Although the information content of visual perception does not resemble an unanalyzed array of pixels, features that are conceptually straightforward, such as density, number, and cluster, might not be directly available to visual analysis. The representation of these features may instead derive both from correlative, visually extractable information and from the conceptually driven interpretation of that information. Distortions of density information produced by adaptation might be expected to provoke a greater change in judgments of numerosity when other kinds of information about numerosity are either unavailable or less influential. This seems to occur with high numerosities, and the simulation data suggest why area information, in itself, underdetermines numerosity at high numerosities. When other reliable sources of information about numerosity are present (at low numerosities), the perceptual distortion of density does not produce a concomitant distortion of numerosity of the same magnitude.

The reciprocal distortions of numerosity and cluster found in the present study suggest that the two dimensions depend in different ways on information about texture density, and that distortions of perceived texture density may be perceptually interpreted as arising from external differences of either numerosity or of cluster, depending on what other relevant information is present. Cluster and density have both been implicated as important variables in determining numerosity. Further investigations of the relations among the three dimensions are in order.

In summary, visual adaptation to dense texture produces three qualitative distortions or aftereffects: (a) a range-independent distortion (decrease) of perceived texture density, (b) a distortion (decrease) of perceived numerosity that increases with numerosity, and (c) a distortion (decrease) of perceived cluster that is greatest for lower numerosities. Moreover, simulations of Allik and Tuulmets's (1991) occupancy model have demonstrated some interesting relationships among the three dimensions studied. On the basis of these facts, I have argued that the distortion of information underlying the perception of density is the primary cause of the aftereffects described in this article; that density information and other relevant kinds of visually available information (e.g., occupied area) have range-dependent influences on the perception of numerosity; and that the distortion of cluster may derive from processes responsible for the perception of density, perhaps in conjunction with information about numerosity. Finally, suggestions for a modification of the occupancy model have been provided on the basis of comparisons between simulations of the model and psychophysical evidence presented here and elsewhere. A feature of the proposed modification of the occupancy model is that it may provide a functional yet quantitative account for all of the parameters in the model by taking into consideration relationships among all three of the texture dimensions studied.

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