Texture density adaptation and visual number revisited

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Burr and Ross [1] have recently proposed that the visual dimension of number is itself directly adaptable. The aftereffect they describe is one that my colleagues and I previously used to investigate the perception of texture density [2–4]. Burr and Ross [1] argue that the effect is new because it concerns visual number, rather than texture density, but they did not report critical tests to support this claim. Here, I shall briefly describe the striking similarity between our prior work and that of Burr and Ross [1], and discuss how some of our results rule out Burr and Ross's [1] interpretation that numerosity, and not density, is at play. I shall also provide a new demonstration that confirms that these effects are based on density, using a display that explicitly dissociates density from numerosity. Taken together, this line of arguments suggests that Burr and Ross's [1] recent study may best be thought of as replicating support within a well-established line of work on texture density.

There is a complex relationship between texture density, area and perceived numerosity. Some theories of numerosity perception have been based on using 'filled' area as the sole basis for numerosity discrimination [5], but a combination of area and density has seemed a reasonable model [3]. Critically, because Burr and Ross [1] did not vary the area of the texture displays to be compared, the numerosity judgments made in their experiments could have been made based on perceived relative texture density. Burr and Ross [1] may state that they had ruled out texture density, but all of the major results in their report replicate prior work by my colleagues in support of a density interpretation, some aspects of which are detailed here.

In a 1997 paper, Alex Huk and I [4] reported our study of the extent to which aftereffects of perceived density could be understood in terms of prior theories of texture size adaptation [6]. We found they could not. We adapted people to differentially dense textures composed of elements with different Fourier spectra and then measured the extent to which judgments of relative density between other textures presented in the same region were affected. Although Burr and Ross [1] describe similar tests using differently sized and oriented bars (and report that the effects are maintained), our stimuli were more segregated in the Fourier domain. For example, rather than black and white squares on a gray background [1], we used high-pass or low-pass filtered black and white elements [4] (see Figure 1 for examples of the textures). Unlike Burr and Ross [1], we found that the aftereffect was systematically reduced (though not eliminated) when the Fourier spectra of adaptation and test stimuli overlapped least. Because apparent density (and numerosity) was reduced even when adaptation was to low-pass elements, our results showed that the effects were not spatial frequency shifts [4]. However, the Fourier specificity we found indicated that the effects were likely due to early cortical texture analyzers rather than abstract numeric representations. These results are consistent with the conclusion that perceived density of texture is an adaptable dimension that affects perceived numerosity, as we originally reported [3].

Because neither we nor Burr and Ross [1] have previously reported a direct manipulation of area, I correct that omission here with some data collected with displays like that shown in Figure 2, where the left texture is more numerous, but the right texture is more dense. This was accomplished by spreading the more numerous dots over a larger area. When the adapting displays thus dissociate number and density, it is the region of greater density that produces greater adaptation. This result is easy to observe using the figure, and was obtained experimentally with participants naïve to the hypotheses. Burr and Ross may respond that coding of visual number is spatially selective. In other words, they may suggest that number per some unit of cortical area is the adapted dimension. But local number is the same concept as density. Density differs from the perception of number of a whole collection.

Rather than requiring that the visual system jump right to a numeric representation, density aftereffects can be explained by earlier visual processes. It is possible to represent a correlate of density as something like statistical kurtosis in the visual image [7] and this may be evaluated at various spatial scales. The computations required to represent this property of texture are probably

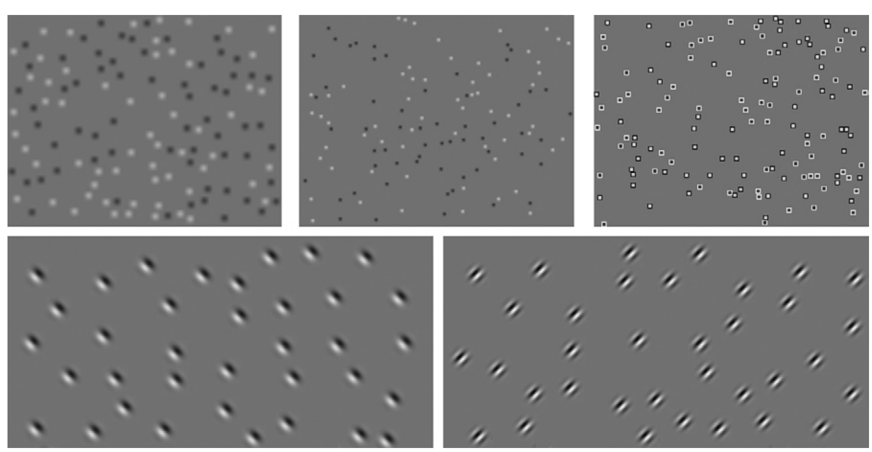

Figure 1. Examples of textures previously used to study transfer across texture types [4].
The textures differed in spatial frequency content (above) and both orientation and spatial frequency (below). Aftereffects were strongest when the test texture was of the same type as the adaptation texture [4]. The elements at the top are more completely segregated in their power spectra than the textures Burr and Ross [1] used for their size manipulation. Huk and I [4] found greater transfer of effects from lower spatial-frequency textures to higher ones than vice-versa.

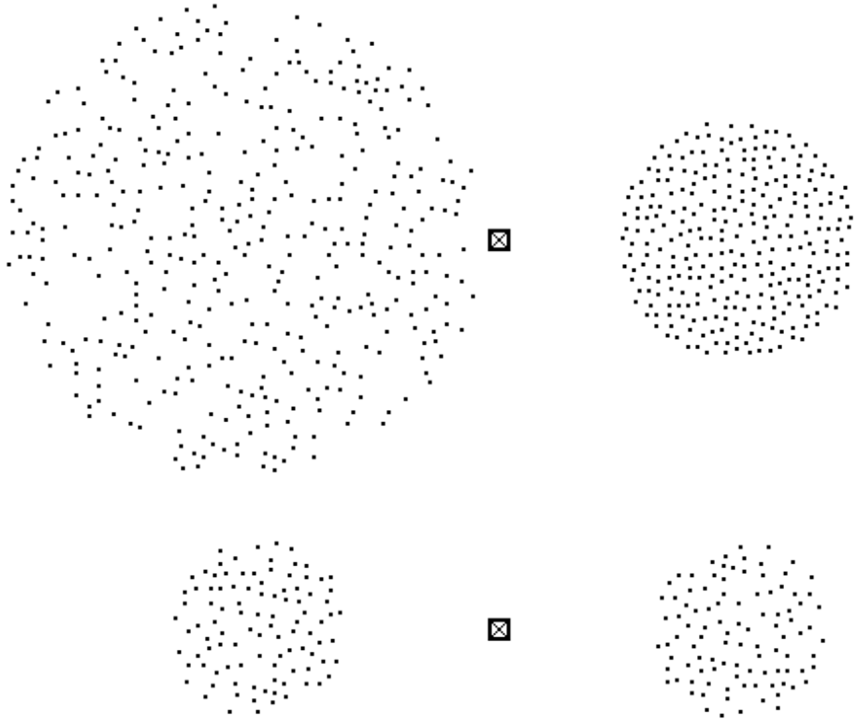

Figure 2. Effects of area manipulation.

When the adapting number is greater on the left (400 versus 290) and the adapting density greater on the right (top texture pair, 11 versus 32 dots degree^{-2}), the perceived numerosity/density of small test fields (lower pair) responds to the difference in adapting density, not number. Three observers naïve to the hypotheses were adapted and tested (elements were white on black, with the small test patches approximately 3 degrees in diameter). To remove effects of local elements, four successive images of statistically equivalent adapting textures preceded each test trial. Blank intervals were added between images to remove effects of apparent motion. Following adaptation, an average of 61 ± 7 (SD) dots presented on the left was adequate to appear equal to 100 dots presented on the right. That is, a texture in the region adapted to the denser side appeared less dense (and therefore less numerous) than dots presented within the region adapted to the more numerous, but less dense texture. The figure may be used to experience the effect by fixating the upper x for about 30 seconds and then glancing to the lower one while comparing the relative densities of the two small texture patches (which are the same patch rotated by 180 degrees). This experiment indicates that density is the adapting dimension.

simple enough to be accomplished by complex cells in primary visual cortex in a manner analogous to contrast normalization in simple cells [8]. Texture density acts very like a kind of second-order luminance contrast [9,10]. Both density and contrast dynamically respond to differences across space [2,11] and time [10]. Aftereffects of density transfer interocularly, however, whereas those of contrast do not, consistent with localization of these effects in complex and simple cells, respectively [2,9]. Because density representation follows contrast normalization, the results of Burr and Ross's [1] investigations of luminance contrast are consistent with our own [9,10]. We think of texture density as one of the sources of information available for judgments of visual number, but believe that Allik's concept of occupancy remains important in lower-numerosity displays and particularly in displays that clearly differ in area.

For purposes of cognition, numeric magnitude is an important dimension, but there is currently no evidence that this is the dimension that is adapted. For example, whereas Burr and Ross [1] refer to evidence that joining pairs of elements into barbells reduces apparent number (without much affecting texture), this point does not extend to adaptation. We have observed that density/numerosity aftereffects following adaptation to textures of paired elements are equally strong whether the paired elements are joined as barbells or not.

In summary, Burr and Ross [1] have elegantly replicated the finding that adaptation of texture density affects the perception of numerosity [3]. It may yet turn out that perceived number itself is indeed adaptable, but cross-modal studies [12] seem a more promising avenue for distinguishing aftereffects of perceived number from retinotopic aftereffects in the early visual analysis of texture density. Although not all cultures have a concept of number, we know that those that do not can nonetheless distinguish magnitudes of stuff. We suspect that they would still be susceptible to the visual aftereffect discussed here.

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