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Visual aftereffects of sequential perception: dynamic adaptation to changes in texture density and contrast

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Abstract

Two new aftereffects are described in which the comparison of successively presented textures can be affected by prior exposure (adaptation) to biased sequences. A dynamic aftereffect of texture density can be produced using changes in non-Fourier texture density (using balanced-dot textures). An analogous dynamic aftereffect is demonstrated for texture contrast. These two effects are dissociated experimentally by the near absence of cross-adaptation. Evidence is also presented that the density effect is not one of texture motion (e.g. expansion/contraction of texture). © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The perceptual registration of spatial information is susceptible to some predictable contextual distortions over time. For example, perceived texture density is subject to successive contrast (aftereffects) (MacKay, 1964; Anstis, 1974; Durgin & Proffitt, 1991, 1996; Durgin, 1995, 1996; Durgin & Huk, 1997). Such susceptibility to aftereffects might be expected to interfere with the sequential comparison of textures. If I first look at a dense texture, my adaptive state is affected, and a texture viewed thereafter would therefore appear different. Can the visual system correct for systematic errors of this sort in normal perception by recalibrating sequential comparison?

Consider the argument for a statistically based recalibratory account of adaptation. In general, when viewing the world with a roving gaze, the statistical characteristics of the stimuli arriving at each part of the retina ought to be roughly equivalent. If they are not, then this may reflect an error in the gain adjustment for that property at that point in the retinotopic cortical map, and compensatory adjustments in the local gain may be called for. On one view, this error correction (Andrews, 1964) involves an error-correcting device, which seeks out inequalities over space. Alternative accounts include Barlow's (1990)(Barlow & Földiák, 1989) thesis that the adaptation process is quite organic to the relevant detectors, and consists of raised inhibition between simultaneously active units ('anti-Hebbian' leaning). Indeed, it may be that certain properties are not distributed equally across space (e.g. with respect to the upper and lower visual field). However, Barlow's (1990) account would allow for the system to adapt itself to this state of affairs — at least with regard to developing the most efficient set of signal analyzers.

This idea of visual system calibration can be easily applied to a typical (spatial) adaptation procedure. Consider adaptation to texture density, as illustrated in Fig. 1. The gaze is fixed in one place (the crosshair), and one portion of the retina (to the left) receives a particular kind of stimulation for an extended period of time. In the adaptation panel of Fig. 1, a portion of the left side of the visual field receives dense texture, while a portion on the right receives sparse texture. Such a circumstance is consistent, visually, with a defect in the gain control mechanism specific to the recording texture

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density in those retinal regions. In a system designed with implicit assumptions about the normal active movement of gaze (and consequent statistical expectations), the steady fixation required by the adaptation procedure may result in adaptive cortical activity normally associated with recalibration across the cortical array. That is, simultaneous comparison across the various regions of the retina will tend to support the implicit hypothesis that the to-be-adapted cortical region is itself to blame for the statistical aberration that adapting stimuli represent. Increased local inhibition among active detectors would, by Barlow's (1990) hypothesis, tend to reduce their subsequent output.

Now consider a rather different sort of adaptation procedure that biases sequential, rather than simultaneous comparison. Imagine that each time one successively compares two fields of texture — as if glancing from one to the other — one finds that the second one viewed is always denser than the first. Such a state of affairs is clearly a statistical anomaly. Back-and-forth comparison (or simply random comparison over time) ought to reveal equal numbers of increases and decreases along any visual dimension. Thus, here again, error-correction processes may be invoked. The mechanism required here may demand more complication than lateral inhibition, because it involves the comparison of two separate visual stimuli presented at the same location. We will call such aftereffects dynamic aftereffects.

Why might successive comparisons be subject to internal error? Short-term aftereffects from gazing at one stimulus might well alter the perception of a second. Or the second might mask the first in some way. The comparison of two stimuli in perception may often require holding representations (of some sort!) of both, and interference between those representations is not out of the question. Just as error correction may be required for accurate simultaneous comparison, so also do the same kinds of theoretical concerns arise for reasonably accurate successive visual comparisons.

To test the hypothesis that sequential visual perception can be altered by adaptation, we adapted observers to sequentially presented pairs of textures in which density was correlated with order of presentation. The paradigm is illustrated schematically in Fig. 2. As predicted, we found that perceptual comparisons of sequentially presented textures were biased (as if recalibrated) following adaptation. In the process of controlling for possible artifacts of contrast, we found similar dynamic contrast aftereffects for changes in

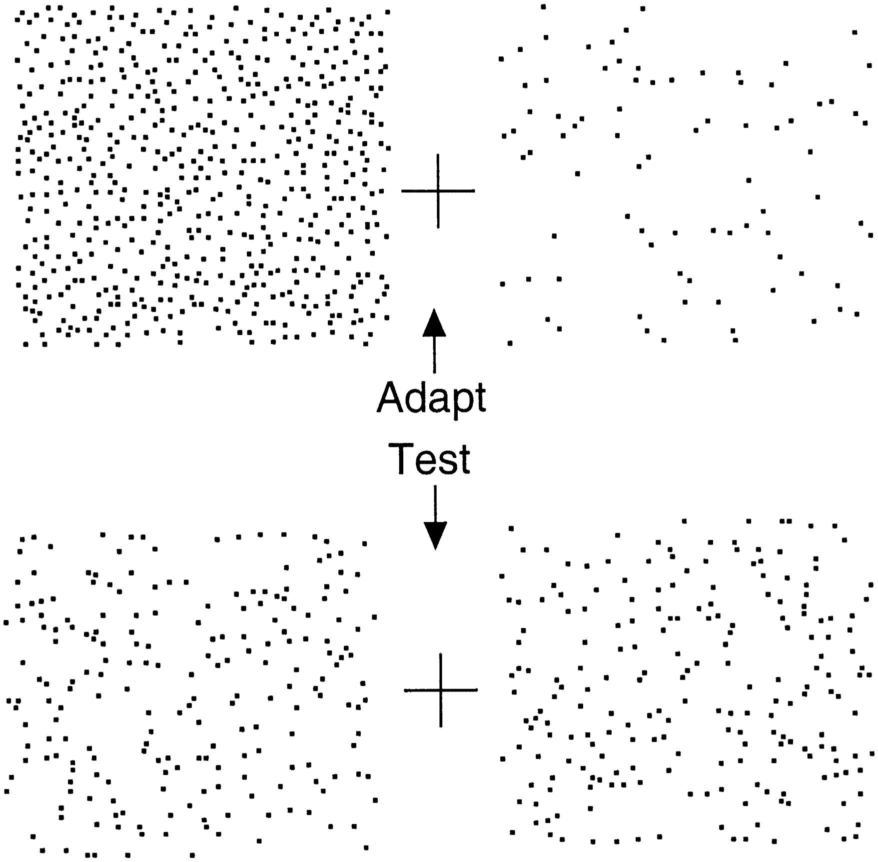

Fig. 1. Demonstration of the texture density aftereffect (Durgin, 1995). Fixate on the upper cross for 30–60 s, then quickly shift gaze to the lower cross. Adaptation to a dense texture on the left side will leave the left texture in the lower panel appearing less dense than the texture on the right.

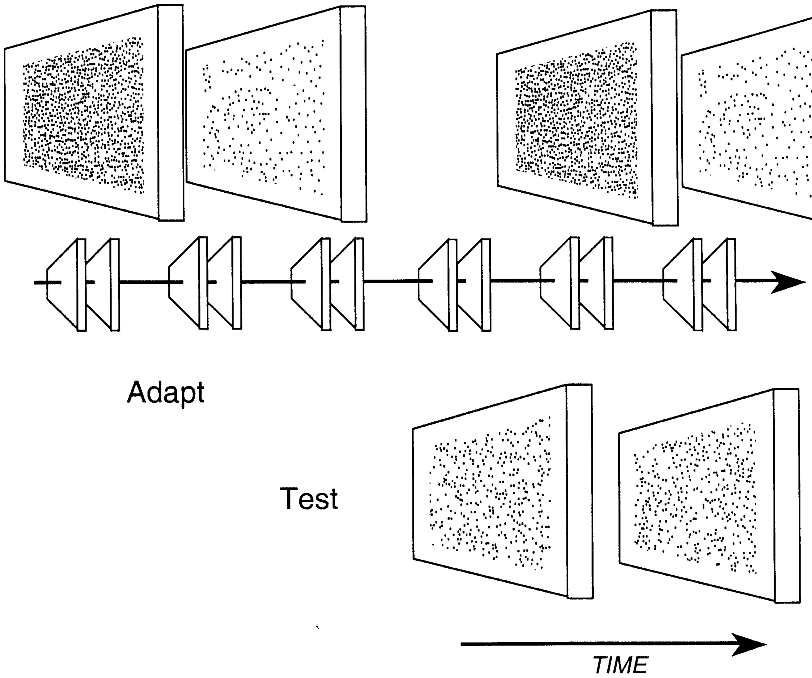

Fig. 2. Schematic illustrations of the stimuli used to generate and test a dynamic density aftereffect are shown. Textures appear in paired sequences in which the first is either always denser or always less dense than the second during adaptation. In the experiments, all textures were newly scattered on each presentation. Analogous sequences can be generated for differences in texture contrast.

texture contrast. As we will report below, further control experiments contraindicate motion-based explanations of these effects.

Walker and Irion (1979)(see also Allan, 1984) have previously reported an aftereffect of perceived auditory duration contingent on temporal order. Our findings indicate that the visual perception of texture can also be adapted with respect to temporal sequence. We interpret this as an adaptation to dimensional change, or dynamic adaptation. Our experiments were inspired by considerations of calibratory demands of normal perception, and the results to be reported here are intended primarily to establish the existence of two phenomena consistent with the adaptation of successive comparison processes.

The simple adaptation of texture density is well documented (Durgin, 1995; Durgin & Proffitt, 1996; Durgin & Huk, 1997). Our experimental design was intended to isolate three variables that might be confounded with density in the present paradigm. Changes in texture density may signal or be confounded with motion in depth from expansion/contraction of texture (Regan & Beverly, 1978), changes in luminance (Anstis, 1967; cf. also Mulligan & MacLeod, 1988), or changes in luminance-contrast intensity.

To help deal with these concerns, we used high-spatial-frequency, luminance-balanced dots (Carlson, Moeller, & Anderson, 1984; Gilden, Bertenthal, & Othman, 1990) as texture elements, because the band-pass spatial frequency content of such textures greatly reduces their effectiveness for motion perception (Gilden et al., 1990). We also used extended inter-stimulus intervals to help eliminate the possibility that the effects were due to first-order motion signals. Balanced dots allow texture density to vary independently of mean luminance and of spatial frequency (Durgin & Proffitt, 1991, 1996; Durgin & Huk, 1997). To control for effects of differences in global contrast, we isolated effects of contrast, per se, by manipulating contrast energy independent of texture density. As a result, a dynamic aftereffect of perceived texture contrast was also found (Experiment 4).

To avoid confusion, it is worth noting that the predicted direction of the aftereffects reported here is opposite to those expected from simple successive contrast. For example, suppose that one were adapted to a pair of textures of which the second is the denser or higher in contrast. According to successive contrast, the first texture of the following test pair might be predicted to be perceived as less dense or less high in contrast than the second texture, as a consequence of being closer in time to the final adapting stimulus (assuming a quickly decaying simple aftereffect). But just the opposite prediction is being made here by the dynamic recalibration account. We suppose that the presentation of sequential adapting textures of which the second is always the denser or the higher in contrast will make the later comparison of equal textures appear to go from denser to more sparse or from higher to lower contrast. Thus, the first of the two comparison textures should seem higher in contrast.

The results of five experiments are reported here. The first experiment demonstrates a dynamic aftereffect in the sequential relative perception of texture density. Experiment 2, which serves as a control for contrast energy artifacts, demonstrates that adaptation to sequences of balanced-dot textures that differ in contrast energy (dot contrast), but not density, does not produce dynamic aftereffects of density. In Experiment 3, we replicated the dynamic density aftereffect finding of Experiment 1 using longer SOAs during adaptation, so that we could more convincingly rule out an interpretation in terms of short-range motion adaptation (e.g. Braddick, 1974).

In the remaining experiments, we studied dynamic aftereffects of perceived contrast. In Experiment 4, we show that the contrast-energy adaptation paradigm (used in Experiment 2) is sufficient to produce a strong dynamic aftereffect of sequentially perceived texture contrast. Finally, in Experiment 5, we tested for dynamic contrast aftereffects following adaptation to changes in density and found small, but reliable, changes. These changes are consistent with the fact that same-element textures that differ in density also differ in total contrast energy, though the converse does not hold.

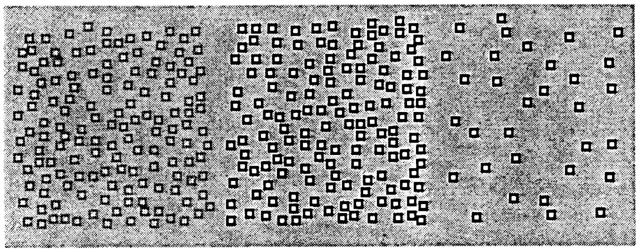

Fig. 3. Three balanced-dot textures. The one to the right is less dense than the middle one. The one to the left is lower in local texture contrast than the middle one, but of the same density. The dots are not photometrically balanced in this reproduction, but are intended to provide a schematic illustration of texture appearance.

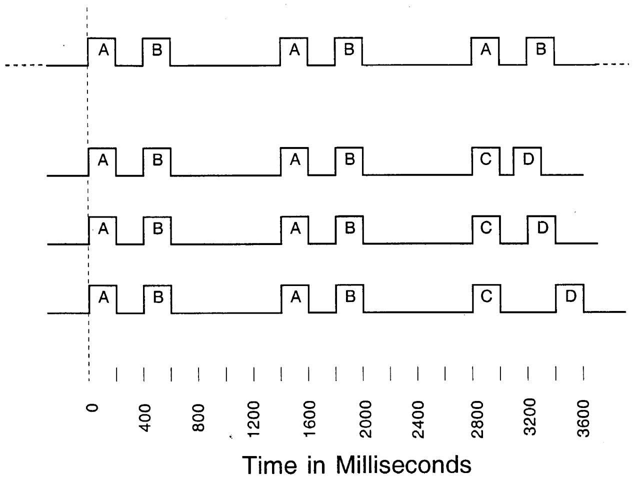

Fig. 4. Schematic illustration of the time course of adaptation and test stimuli is shown here. Initial adaptation consisted of 120 double pulses, three of which are depicted in the top row. A and B were the respective adapting textures (either dense and sparse, or high-contrast and low-contrast). A test trial included two double pulses of adaptation, and a third pair of textures, C, and D, for comparison. The ISI between C and D was either 100, 200 or 400 ms. All ISIs were doubled for Experiment 3.

2. General methods

The observers for each experiment included both authors as well as, for Experiments 1–4, one or two of several observers who were naïve to the experimental hypothesis.

The displays were generated and presented on a SUN SPARCstation equipped with a 21 inch monitor with 40 pixels/cm screen resolution.

The texture stimuli were composed of square luminance-balanced dots, which were themselves composed of a bright central region (2×2 pixels) and a 1-pixel-wide annulus. These elements were scattered randomly against a background gray of 12 cd/m^2, within a region 400×400 pixels, or about 12×12 deg of visual angle at the viewing distance of 45 cm. The only constraint on the randomized placement was that the dots could not touch or overlap. The peak spatial frequency of such textures is determined by the elements themselves and was about 8 cycles per degree. In Experiments 2, 4, and 5, the contrast of the individual dots was manipulated by simultaneously lowering the luminance of the center and raising the luminance of the annulus so that the space-average luminance remained constant, as assessed photometrically. This is illustrated in Fig. 3. Our precise definition of contrast values for balanced-dot textures will be presented in the introduction to Experiment 4. The adaptation densities were 5.6 dots/deg^2 (dense) and 1.4 dots/deg^2 (sparse), when density-varied. Adaptation contrasts were $\sim 100\%$ (high) and 25% (low) when contrast varied. High contrast or high density was the default when the other dimension was being varied.

Adaptation sequences for Experiments 1, 2, 4, and 5 consisted of a 200 ms exposure to one texture, followed 200 ms later by a 200 ms exposure to a second texture. The sequence of events is depicted in Fig. 4. The ISI was changed to 400 ms in Experiment 3. In Experiments 1, 3, and 5, the two textures differed systematically in texture density, but not in local contrast. In Experiments 2 and 4, they differed in contrast, but not in actual density. There were 120 initial presentations of the adaptation sequences, and there were two further adapting presentations just prior to each test stimulus. All observers were adapted to each direction of change in sessions performed on separate days.

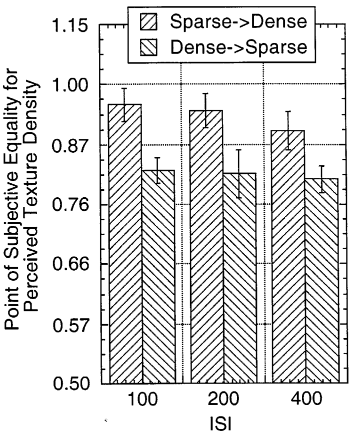

Fig. 5. Average PSEs for dynamic texture density following dynamic adaptation to increases or decreases in texture density are plotted as a function of ISI for Experiment 1. The Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

Measurement of the aftereffects of adaptation was accomplished by estimating points of subjective equality (PSEs) for sequentially presented textures. In each experimental session, the PSEs were measured for texture density (Experiments 1, 2, 3) or for texture contrast (Experiments 4, 5) using a staircase method. On each test trial, the observer simply indicated whether the first or second of two textures appeared to be denser (Experiment 1, 2, 3) or higher in contrast (Experiments 4, 5). The ISI between the two textures was varied systematically, but the interval between separate adaptation pairs, and between the final adaptation pair and the test pair was maintained at 800 ms.

In all, 12 PSE measurements were made for each experimental session by 12 interleaved staircases. Two separate staircases produced duplicate estimates for each observer of PSEs for density (or contrast) to each of two standard values of density (2.8 or 4.2 dots/deg^2) or contrast (50 or 68% contrast) at each of 3 ISIs (100, 200, and 400 ms). During adaptation, high values of contrast ($\sim$ 100%) were the default when density was being varied and high values of density (5.6 dots/deg^2) were the default when contrast was being varied.

Each staircase began at objective equality. Depending on the observers' judgments, the second texture in the sequence was adjusted in density (or contrast) so as to reduce perceived differences. Initially, larger step sizes were used, but these decreased after two 'turns' of the staircase to 5% of the standard density value, or 1 unit of contrast, as defined below. Thereafter, six further turns in the staircase were averaged to estimate the PSE.

Data analysis was performed on logarithmically transformed values of density and contrast. In fact, PSEs were expressed as differences in log space between the PSE and objective equality. This was tentatively decided in advance because density aftereffects are typically realized as proportional distortions, thus producing a constant logarithmic difference in perceived magnitude at all standard values (cf. Durgin, 1996, for an extended discussion). Although it was reasonable to assume that contrast aftereffects might be similar, we sought empirical confirmation of this before conducting our analyses. Indeed, changes in contrast at PSE tended to be proportional to the absolute contrast value being tested in Experiments 3 and 4, justifying a logarithmic transform. Differences between the logarithms of two quantities are equivalent to the logarithm of the ratio between those quantities. In reporting these values, we will always refer to the logarithm of the underlying ratio.

Because the use of different standard values served the primary purpose of testing for an appropriate transform of our data, PSEs for different values were subsequently combined prior to the analysis of the data, as were the duplicate staircase data. Consequently, for each adaptation condition, only one number was entered into the overall analysis at each of the three ISIs.

3. Experiment 1: a dynamic aftereffect of texture density

In the first experiment, we sought simply to measure the change in sequential PSEs for density following adaptations to increasing density and to decreasing density. It was expected that adaptation to pairs in which density increased, would lead to the perception that sequentially presented pairs of objectively equal textures would seem to decrease in density. Thus, we predicted that PSEs following adaptation to increases would be elevated (to compensate for the apparent decrease) relative to those following adaptation to decreases.

Four observers participated, two of which were naïve to the purpose of the experiment. The data from these four observers were analyzed using a 2 (direction of adaptation: Dense $\rightarrow$ Sparse or Sparse $\rightarrow$ Dense) × 3 (ISI: 100, 200, or 400 ms) repeated-measures ANOVA. Group data are shown in Fig. 5. As expected, the analysis revealed that PSEs in the Sparse $\rightarrow$ Dense condition [$M = \log(0.93)$] were higher than those in the Dense $\rightarrow$ Sparse condition [$M = \log(0.81)$], [$F(1,3) = 10.281$, $P < 0.05$]. Surprisingly, however, both sets of PSEs were less than objective equality. We therefore also recorded PSEs for sequentially presented textures without any adaptation, to establish baseline performance standards. However, the average PSEs in our baseline condition [$M = \log(0.97)$], while quite close to objective reality, were somewhat higher than PSEs in either adaptation group. It is possible that the adapta-

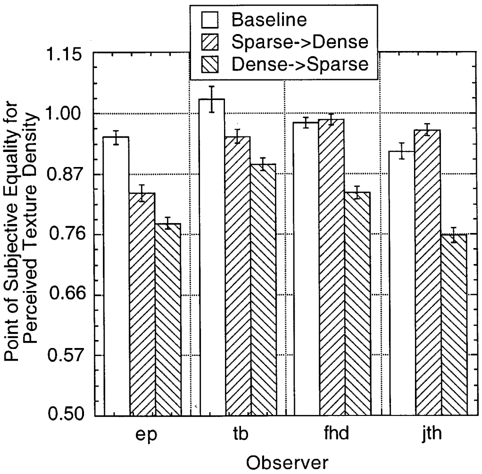

Fig. 6. Average PSEs for dynamic texture density following dynamic adaptation to increases or decreases in texture density are plotted for each observer in Experiment 1. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

tion process promotes a general decrease in baseline against which the different adaptation directions act — a point of view supported by the results of Experiment 2.

One further aspect of the data that deserves note is a marginal effect of ISI, such that PSEs appear lowest for the longest ISIs [$F(2,6) = 3.5$, $P < 0.10$]. However, there was no evidence of a statistical interaction between the effects of adaptation direction and ISI, [$F(2,6) < 1$]. In other words, the amount of difference between the two different adaptation directions was not appreciably lessened at an ISI of 400 ms. This suggests that the comparison mechanisms subject to this aftereffect may have a rather wide temporal bandwidth.

The individual patterns of data for each subject all accorded with these conclusions. Fig. 6 depicts the individual adaptation data of Experiment 1, collapsed across ISI.

4. Experiment 2: no dynamic density aftereffect following adaptation to changes in contrast energy

Changes in texture density in balanced dot textures do not change the spatial frequency content of the textures (cf. Durgin & Huk, 1997). However, adding

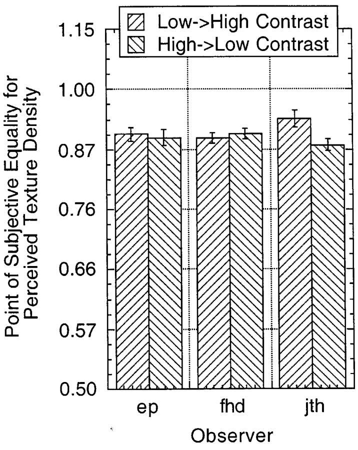

Fig. 8. Average PSEs for dynamic texture density following dynamic adaptation to increases or decreases in texture contrast are plotted for each observer in Experiment 2. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

dots does add more contrast energy. In Fourier terms, the power spectrum of a balanced dot texture varies in amplitude, though not shape, with variations in density. Could the dynamic density aftereffect actually be due to dynamic contrast adaptation? After all, Anstis (1967) already showed that one could obtain aftereffects to continuous changes in luminance energy. To test this alternative account, a simple control experiment was undertaken to determine whether dynamic adaptation to textures that differed in contrast energy, but not in density, would none the less produce dynamic density aftereffects.

To accomplish this, we simply varied the contrast energy of the individual dots in a texture, as indicated schematically in Fig. 7. In other words, the adaptation stimuli were now all of equal density, but represented dynamic changes in texture contrast (see also Fig. 3). The measurement of dynamic density comparisons remained as in Experiment 1. The two authors and one of the naïve observers from Experiment 1 participated.

A 2 (Adaptation Direction: High to low contrast or Low to high contrast) × 3 (ISI: 100, 200, or 400 ms) repeated-measures ANOVA was performed on the dynamic density aftereffect scores collapsed across absolute density. Individual results are shown in Fig. 8, collapsed also across ISI. As is obvious from the figure,

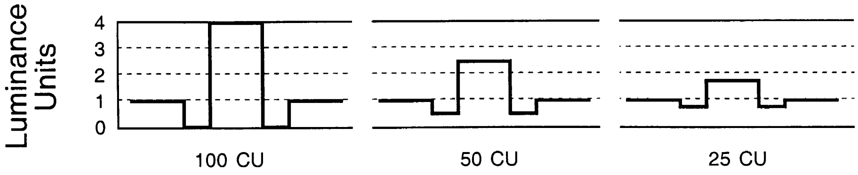

Fig. 7. Schematic luminance profiles of balanced dots are shown here for dots of various contrast values. See text for an explanation of contrast units (CU) used.

there was no reliable dynamic density aftereffect following adaptation to changes in texture contrast. That is, there was no effect of Adaptation Direction on PSE [$F(1,2) < 1$, n.s.]. There was also no effect of ISI [$F(1,2) < 1$, n.s.]. Observer JHT shows the only evidence of dynamic aftereffect in the correct direction, but the magnitude is quite small compared to that found for JHT in Experiment 1. Of some note is the fact that density matches show consistent bias for all observers. Fewer dots are needed in the second stimulus, for two textures presented sequentially to appear subjectively equal. Indeed, the average PSE is a geometric mean ratio of 0.90. This value is consistent with the trend for aftereffect scores in Experiment 1 all to be somewhat less than a ratio of 1.

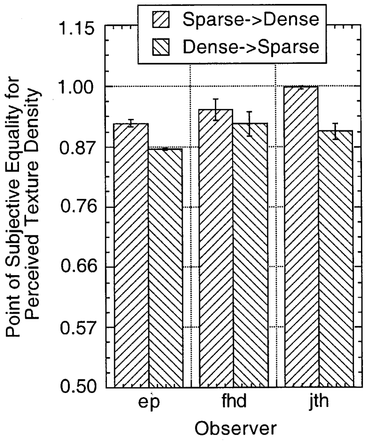

Fig. 9. Average PSEs for dynamic texture density following dynamic adaptation to increases or decreases in texture density are plotted for each observer in Experiment 3. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

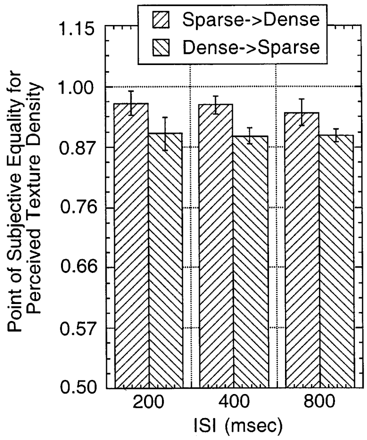

Fig. 10. Average PSEs for dynamic texture density following dynamic adaptation to increases or decreases in texture density are plotted as a function of ISI for Experiment 3. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

In any case, the hypothesis that dynamic density adaptation was due to differences in amplitude, or power spectra, was not supported by the present results. Textures differing in contrast do not produce dynamic density aftereffects.

5. Experiment 3: the dynamic density aftereffect generated with a longer ISI during adaptation

With normal luminous dots, changes in texture density could be statistically related to motion signals for expansion or contraction. Changes in density are confounded with changes in inter-dot distances. Luminance-balance dots are a poor stimulus for the motion system (cf. Gilden et al., 1990), which is partly why we employed them here. Indeed, no impression of motion was ever reported or observed by us in our displays. None the less, front-end non-linearities in the visual system make it difficult to be confident that photometrically balanced dots can be counted on to remove all motion signal. We used a range of ISIs during the test phase of Experiment 1 to see whether the effects would be limited to particular ISIs (100, or possibly 200 ms), such as those associated with the short-range motion system (Braddick, 1974), but little evidence for such limitations was found. Indeed, our shortest ISI, of 100 ms, actually entails an SOA of 300 ms, which is outside the range of short-range motion.

None the less, in this experiment, we sought to push the logic further by having a longer ISI during adaptation. Although longer ISIs are also less likely to be resolvable by any system devoted to calibrating vision over time, they are particularly likely to eliminate short-range motion signals. The experiment was identical to Experiment 1 except that all ISIs were increased by a factor of 2. This meant that in addition to adjusting the adapting ISI from 200 to 400 ms, we shifted the ISIs at test. In effect, we eliminated the ISI of 100 msec and introduced an ISI of 800 ms (SOA of 1000 ms).

The observers were the same as in Experiment 2. All had also participated in Experiment 1. As in Experiment 1, all three individuals showed evidence of dynamic adaptation. The relative PSEs for the three observers are shown in Fig. 9. A 2 × 3 repeated-measures ANOVA showed a marginal effect of Adaptation Direction in the predicted direction [$F(1,2) = 11.04$, $P = 0.08$]. There was no reliable effect of ISI, [$F(1,2) < 1$, n.s.], nor was there a reliable interaction between ISI and adaptation direction [$F(1,2) < 1$, n.s.]. Indeed, as is shown in Fig. 10, the differences in PSEs due, by hypothesis, to differential dynamic aftereffects, appear to be about equal at all ISIs from 200 to 800 ms.

In conclusion, even with an ISI of 400 ms during adaptation, evidence for dynamic density aftereffects was found at ISIs from 200 to 800 ms. Although the

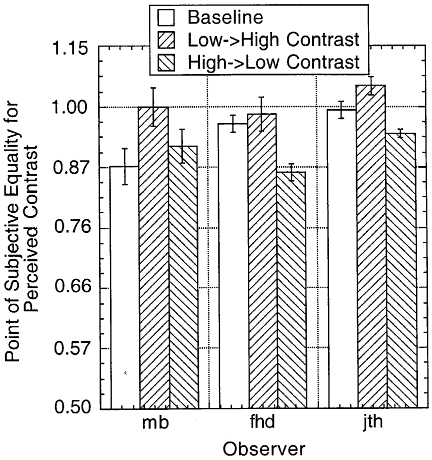

Fig. 11. Average PSEs for dynamic texture contrast following dynamic adaptation to increases or decreases in texture contrast are plotted for each observer in Experiment 4. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

aftereffects appear weaker than those of Experiment 1, this is consistent with an adaptive recalibration account. Indeed, almost any account would predict decreased effects at longer intervals. However, the fact that a substantial aftereffect is still generated even when ISIs have increased to 400 ms (and SOAs to 600 ms) seems to rule out the short-range motion system. The relative insensitivity to ISI at time of test also seems inconsistent with an account of dynamic density aftereffects in terms of motion aftereffects to expansion or contraction. The underlying process seems able to handle rather long intervals between the two target stimulus textures. This is most consistent with a comparator process, such as might be used in normal vision to compare successively fixated displays.

6. Experiment 4: demonstrating a dynamic aftereffect of perceived texture contrast

What about the manipulation of texture contrast? Experiment 2 showed that adapting to biased sequences of texture that differed in luminance contrast failed to produce a dynamic density aftereffect. To test for dynamic adaptation of perceived contrast, in the present experiment, we simply altered the measurement phase of the paradigm, so that all test textures were equal in density, but differed in contrast. The staircase procedures described in the general methods section were then applied to the luminance contrast of the individual dots in the textures, so that PSEs for successive relative contrast could be measured.

Each balanced dot is composed of 16 pixels (four light in the center, and 12 dark as the annulus) against a background of gray. The contrast of the dot may be defined as 100% when the dark pixels are black (~ 0), and the light pixels are set to the maximum setting (white). If the average luminance (to which the background gray is matched) is defined as L, then the white pixels are each 4L. To lower the contrast of the dot while maintaining the same space-average luminance requires that the dark pixels be made lighter as the light pixels are made darker. The background gray stays the same, however, so that average luminance is held fixed. As the light pixels approach L from above, the dark pixels must also approach it from below. Clearly, when all pixels are L, contrast is zero. The scale of contrast employed in this paper simply considers the luminance value of the light center of the dots. At its maximum, 4L, it is 100 contrast units (CU), and at its (theoretical) minimum, L, it is 0 contrast units. Between these values, we simply interpolate linearly, so that, for example, 3L is 67 CU, and 2.5L is 50 CU. The 25% contrast used in Experiment 2 as the dim adapting stimulus, thus had a center luminance value of 1.75L (see Fig. 7) Individual luminance values for balanced dots were carefully calibrated to the necessary CU values and periodically rechecked.

As described in Section 2, the adapting textures for this experiment were all high-density textures, and were either 100 or 25 CU. The test textures were of the same high density. The standard contrast values used for testing were 50 and 68 CU. PSEs were again expressed as logarithmic differences between CU values at PSE. They are plotted in the figures as ratios on logarithmic scales, just as was true for density. In all details, save the substitution of contrast for density, the experiment was identical to Experiment 1. The two authors and one student naïve to the purpose of the experiment served as observers.

As can be seen from Fig. 11, all three observers demonstrated evidence of a dynamic aftereffect in the perception of texture contrast. A 2×3 repeated-measures ANOVA showed that, as predicted, PSEs were higher for Low Contrast → High Contrast adaptation than for High Contrast → Low Contrast adaptation [$F(1,2) = 70.0$, $P < 0.05$]. There were no reliable effects of ISI [$F(2,4) = 2.25$, $P > 0.10$]. Nor was their a reliable interaction between Adaptation Direction and ISI [$F(2,4) = 2.48$, $P > 0.10$].

This dynamic contrast aftereffect may be related to the dynamic luminance aftereffect reported by Anstis (1967). Taken together with the findings of dynamic density aftereffects in Experiments 1 and 3, this suggests that general processes of temporal calibration may operate in the visual system for certain scalar properties, such as luminance, contrast, and texture density. Anstis (personal communication) has attempted to look for similar dynamic aftereffects in the spatial frequency domain, but without success.

7. Experiment 5: density as global contrast

Much as Experiment 2 tested for dynamic aftereffects of density following dynamic contrast adaptation, we wanted to test for dynamic aftereffects of perceived contrast following dynamic density adaptation. The logic here is slightly different, however, because balanced-dot textures that differ in density do, in fact, differ in global contrast energy (if the elements themselves are identical). Therefore, the present experiment can be understood as a test for whether the dynamic contrast aftereffects demonstrated in Experiment 4 are specific to local dot contrast, or are also sensitive to global contrast energy. Dynamic density adaptation was as in Experiment 1, and dynamic contrast aftereffects were assessed as in Experiment 4.

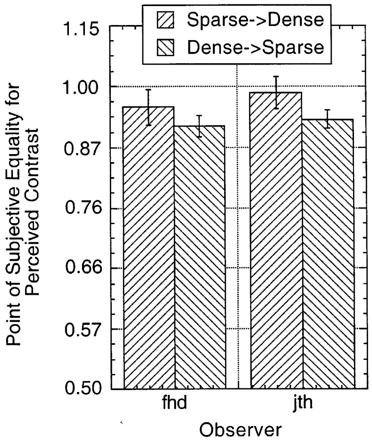

Fig. 12. Average PSEs for dynamic texture contrast following dynamic adaptation to increases or decreases in texture density are plotted for each observer in Experiment 5. Direction of adaptation is indicated in the legend. The Y-axis indicates the objective ratio at PSE on a logarithmic scale. Error bars represent standard errors of the means.

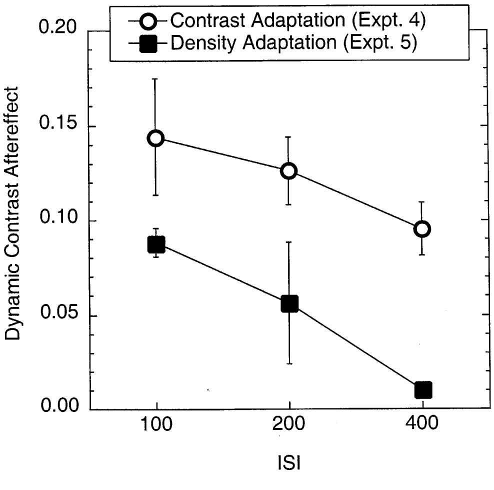

Fig. 13. Dynamic texture contrast aftereffect size as a function of ISI for Experiments 4 (dynamic texture contrast adaptation) and 5 (dynamic texture density adaptation). Aftereffect size is computed as the logarithmic difference between post-adaptation PSEs following adaptation to an increase within a dimension and to a decrease within a dimension. A value of zero on the y-axis represents no aftereffect. A value of 0.15 represents a ratio of 1.16. Averaged data of two observers (F.H.D. and J.T.H.) is shown. Error bars represent standard errors of the means.

Only the two authors served as observers for this Experiment, which did not leave enough degrees of freedom for a repeated-measures ANOVA. The results are shown in Fig. 12. There is, evidently, a weak aftereffect. However, a more complete picture of the data is shown in Fig. 13. For a more direct comparison with Experiment 4, we have plotted a different kind of measure of aftereffect as a function of ISI for both experiments together. Rather than potting the PSEs themselves for the two different directions of adaptation, we have plotted the difference between them. That is, for observers JTH and FHD combined, we plot the average difference between the two directions of adaptation at each test ISI, for each experiment (dynamic contrast adaptation and dynamic density adaptation). The graphs depict these difference in terms of their natural logarithms, so as to avoid confusion with the other plots. What is most striking about the data are that there is a dramatic effect of ISI in the data from Experiment 5, such that at the longest ISI, there is essentially no aftereffect at all. Although the data from Experiment 4 show a trend for a decreased aftereffect, as well, at long ISIs, there was clearly a strong dynamic contrast aftereffect following dynamic contrast adaptation.

Why should adaptation to dynamic changes in density produce dynamic aftereffects of perceived contrast? Our supposition was that changes in density actually do entail differences in global contrast energy. However, why should these effects be limited to short-ISI test stimuli? One possibility is that global and local contrast differences are confusable at short ISIs, leading to a substitution of one property for the other. It may be that separate time-courses apply to these two processes with comparison of global contrast preceding that of local.

8. General discussion

The results of the experiments reported here indicate that the sequential visual perception of simple texture features, such as density and contrast are subject to aftereffects. We have called these 'dynamic aftereffects' to indicate that they seem to refer to a comparison among pairs of stimuli dynamically represented in the brain. We have argued that these effects may arise as a calibratory process in sequential perception, based on adaptation to statistically biased input. We do not argue that calibration is complete, but only that the adapted state changes in the appropriate direction. It is clear that the two visual dimensions of density and contrast are distinct as evidenced by their similar, but distinct dynamic adaptations.

These aftereffects are somewhat like contingent aftereffects (cf. Durgin, 1996; Durgin & Proffitt, 1996), but are also rather unlike them. In the McCollough effect, perceived color is dependent on spatial orientation. In the present effect, the contingency would appear to be on relative time — relative perceived density is affected by relative order in time. Is relative order in time an explicit perceptual dimension? Instead of depending on the construct of contingent adaptation, we have interpreted these dynamic aftereffects as the recalibration of sequential perception for purposes of accurate successive comparison. The general goal of recalibration can be applied to dynamic aftereffects as well as to contingent aftereffects.

However, recalibration theories are not unique to these complex forms of adaptation. As we explained in Section 1, a recalibration account may also apply to simple adaptation of a single feature. Indeed, although many forms of adaptation are normally rather short term, the possibility that more permanent shift may occur with prolonged exposure is unavoidable for certain kinds of adaptation. Such is the case, for example, with adaptations to some of the optical distortions produced by eye-glasses. A new pair of glasses will sometimes produce prominent color fringes and distortions of space — especially in the periphery. These distortions fade in time and, ultimately, disappear for good, as the visual system becomes accustomed to this state of affairs (cf. Held, 1980).

Conversely, models of adaptation based on simple metabolic fatigue appear less plausible than first thought. Spatial frequency aftereffects, for example, which normally decay with some rapidity, are preserved intact if the eyes are kept closed for some time (Thompson & Movshon, 1978). The same seems to apply to the McCollough effect (MacKay & MacKay, 1975). Moreover, some forms of adaptation demonstrate very long-term aftereffects — lasting for days (Wolfe & O'Connell, 1986). The McCollough effect has been reported to last for months (Jones & Holding, 1975).

Treisman (1984a,b) has suggested that contingent aftereffects, generally, and sequential aftereffects (e.g. that reported by Allan, 1984), in particular, may be regarded as cases of criterion setting effects at a decision-making stage. Such a theory, cast generally enough, may be an adequate description of any changes in perceptual decisions. After all, even the most peripheral of visual detectors may be regarded as making 'decisions' and having 'criteria.' However, to interpret such a theory as arguing for central 'cognitive' site as the locus of adaptation in the present case would seem to suggest that these effects ought to be indifferent to eye of origin. In fact, in a follow-up study, Durgin (submitted for publication) has shown that the dynamic contrast aftereffects do not show any interocular transfer, indicating a rather peripheral cite of adaptation.

The dynamic aftereffects reported here are not large (though 15% distortions are not small, either), and we do not know how long they persist. What we do expect is that the visual system must find a way to control for temporal drift. Anstis (1967) showed that the system does adapt to drifts in luminance. We have shown rather analogous effects for texture contrast and texture density. These effects do not seem to be motion aftereffects, though they are dynamic aftereffects. Anstis found that the luminance-ramp aftereffect did not transfer interocularly. Durgin (2001) has found that the dynamic aftereffect of texture contrast is similarly monocular. Evidently, it can be accomplished by fairly early (monocular) units. Dynamic texture density aftereffects, however, appear to be binocular, as are simple texture density aftereffects (Durgin, 2001). We therefore conclude that the visual system seems to be able to normalize or recalibrate the sequential perception of these forms of scalar information when confronted with evidence of a bias in sequential perception.

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