A phase-specific adaptation effect of the square-wave grating

Richard V. Sansbury, Jane Distelhorst, and Sarah Moore

The existence of wide-band, phase-specific channels in the human visual system has been suggested in recent investigations. We used a number of adapting gratings to test for phase-specific adaptation effects. Observers were asked to discriminate between a simple 3 cpd sine-wave grating, (3), and a complex grating composed of this (3) plus a 9 cpd grating combined in one of two phases: peaks-subtract, (3,9:0), or peaks-add, (3,9:π). The results show a significant phase-specific adaptation effect. That is, following adaptation to a square-wave grating, discrimination performance for (3,9:0) vs. (3) deteriorated significantly more than for (3,9:π) vs. (3). Adaptation to the first two harmonics of the square-wave, (3,9:0), or a 3 cpd triangle-wave grating failed to produce phase-specific adaptation effects that reached significance.

Key words: spatial frequency channels, adaptation, phase-specificity, square-wave grating, triangle-wave grating, masking

Spatial information processing by the visual system has been a topic of keen interest over the past 10 years. There are numerous feature analyzers employed in this task, some of which have been dubbed narrow-band channels—a channel being defined as a hypothetical mechanism that responds best to stimuli called gratings. A simple grating is a luminance pattern that varies sinusoidally in one dimension but remains constant in the orthogonal dimension. For example, a vertical grating contains vertically oriented light and dark stripes that appear to fade (or fuzz) into each other. The number of light/dark stripe pairs in each degree of visual angle defines the spatial frequency of the grating.

One important characteristic of a channel is the degree to which it is "tuned," i.e., how selectively it responds to spatial frequencies. In general, the range of frequencies to which a channel will respond is referred to as the channel bandwidth. Unfortunately, there are different rules for specifying exactly which spatial frequencies should be included in a measure of bandwidth. In this report, if a channel responds to a range of frequencies no greater than 1 octave (a factor of 2), it will be called a narrow-band channel. Otherwise, the channel will be referred to as wide-band.

In recent years, a growing number of investigators have suggested that the visual system contains wide-band channels. In particular, it has been suggested that some of these analyze the stimulus for the presence of sharp edges (e.g., see ref. 8). According to Fourier's theorem we know that many stimuli can be constructed by combining sinusoids of the appropriate frequency, amplitude, and phase. This means an edge, or series of edges, can be thought of as a collection of sine-wave gratings. For example, an f
cycle per degree (cpd) square-wave grating of unit amplitude can be constructed from (or is equal to) the following:

$$\sum_{n=1}^{\infty} B \frac{4}{\pi n} \cos nf$$

where $B = 1$ for $n = 1, 5, 9, \ldots$; $B = -1$ for $n = 3, 7, 11, \ldots$; and $B = 0$ for even $n$.

Luminance profiles for the first two components of a square-wave grating are graphically illustrated in $a$ and $b$ of Fig. 1. Part $c$ shows these components combined in the square-wave phase. Part $b$ has been shifted by half of its period, a 180° phase shift. Note how a change in phase can drastically alter a grating’s luminance profile.

A channel designed to analyze stimuli for the presence of square-wave gratings would, ideally, respond vigorously to a square-wave grating and very little to any other stimulus. In other words, the channel would respond selectively to stimuli that contained the appropriate pattern of sine-wave frequencies, with the appropriate phases and amplitudes. Such channels could be described as frequency-, phase-, and amplitude-specific. The experiments reported here were designed to test primarily for phase-specificity in wide-band channels.

If, in the human visual system, there are phase-specific channels, it might be possible to adapt them. Indeed, some examples of phase-specific adaptation have already been reported. In what follows we report new evidence of such adaptation, providing additional support for the notion of wide-band, phase-specific channels.

**Methods**

Observers were asked to discriminate between gratings whose luminance distributions varied in only one dimension, the horizontal. Fig. 1 illustrates the relative periodicities of these gratings as well as the waveform and relative periodicities of the gratings used as adapting stimuli. Let a simple sinusoidal grating of frequency $f$ cpd be denoted by $(f)$ and a complex grating formed by combining $(f)$ and $(3f)$ be denoted by $(f, 3f; \Phi)$, where $\Phi$ specifies the phase relationship of $(f)$ and $(3f)$. With this notation, if $(f)$, shown in $a$, and $(3f)$, shown in $b$, are combined in the phases they occupy in the $f$ cpd square-wave, shown in $e$, the luminance peaks of $(f)$ coincide with luminance troughs of $(3f)$ and $\Phi = 0$ (the resulting complex grating denoted by $(f, 3f; 0)$, is shown in $c$). Shifting the phase of $(3f)$ by $\pi$ radians aligns some of its peaks with those of $(f)$ and produces $(f, 3f; \pi)$, shown in $d$. This is the phase relationship, but not relative amplitudes, of $(f)$ and $(3f)$ in the $f$ cpd triangle-wave grating profile shown in $f$.

Observers were asked to discriminate either $(f, 3f; 0)$ or $(f, 3f; \pi)$ from $(f)$. That is, they were asked to discriminate either the peaks-subtract or the peaks-add combination of $(f)$ and $(3f)$ from $(f)$ alone. We used a temporal two-alternative forced-choice procedure. The two observation intervals, cued by tone bursts, had a duration and a separation of 250 msec. During the time remaining in the 6 sec trial, the observer responded and received immediate auditory feedback as to the correctness of his choice. Trials were presented in blocks of 50, with four to eight blocks comprising an experimental session. Prior to each block, observers were given practice until they felt confident to their criteria. $(f)$, presented in both...
Fig. 2. Unadapted log contrast threshold of (9) for four observers under three conditions. Sine-waves, ~, indicate discrimination of (9) from a blank field; •, discrimination of (3,9:0) from (3); A, discrimination of (3,9:π) from (3). Error brackets are shown for standard errors greater than 0.018 log units. For values smaller than this, ±1 standard error falls within the data symbols.

observation intervals, had a frequency of 3 cpd and contrast of 3.16%. Grating contrast is defined as follows:

\[ C = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} \]

where C is contrast; \( L_{\text{max}} \) is maximum luminance of grating; \( L_{\text{min}} \) is minimum luminance of grating. Percent contrast, \( \%C \), is 100C.

The contrast of (3f), the 9 cpd grating presented in one observation interval only, was varied in order to estimate the value that would yield 75% correct discrimination of (3,9:0) from (3). The experimenter would set the contrast of (9) to a value expected, on the basis of practice session data, to produce a correct discrimination score between 65% and 85%. The contrast of (9) in the next block of trials was determined by performance in the previous block. For example, if the observer did better than 75% correct in the first block, contrast of (9) would be 0.1 to 0.2 log units less in the next. In this way, discrimination scores greater than, and less than, 75% correct were obtained. The contrast of (9) that should result in a 75% correct discrimination score was then estimated by interpolation. This contrast of (9) will be referred to as threshold contrast. At least two sessions were run each day. In the first session unadapted threshold contrast was estimated for both peaks-add, (3,9:π), and peaks-subtract, (3,9:0), combinations of (9) and (3). In the second, or adaptation, session an adapting grating appeared for 3.35 sec in each trial; it was removed 0.7 sec before the first observation interval and reappeared 1.2 sec after the second. Prior to data collection, observers were exposed to 3 min of these adaptation trials with blank observation intervals. The measurement procedures of the baseline session were then repeated under the second session's adaptation conditions. Any significant change in log contrast threshold was taken as evidence of an adaptation effect. A number of adapting gratings were used: a 3 cpd, 34% contrast triangle-wave; a 3 cpd, 21.6% contrast square-wave; its 3 cpd, 27.6% contrast fundamental; its 9 cpd, 9.1% contrast third harmonic component; and a (3,9:0), formed by combining the square-wave's fundamental and third harmonic in peaks-subtract, or square-wave, phase.

Gratings were generated in a conventional manner; the luminance of an oscilloscopically presented raster display was modulated by the output of a number of function generators, all of which were synchronized to the sweep of an oscilloscope. The frame rate and mean luminance of the display screen were approximately 200 Hz and 1.5 foot-lamberts, respectively. Calibration with a Photovolt photomultiplier tube showed a linear relationship (within 2%) between grating contrast and z-axis modulation voltage up to a contrast of about 60%. Observers viewed the display binocularly with natural pupils from a distance of 95 cm. From that distance the rectangular display had a vertical and horizontal extent of 3.3° by 4.8° and was centered in a 19.1° surround matched for approximate color and luminance. The rest of the room was only dimly illuminated.

Results

Fig. 2 shows log contrast threshold of (9) for both phase combinations of (3) and (9) and for discrimination of (9) from a blank field (an
Fig. 3. Effect of adaptation on discrimination of \((3,9; \Phi)\) from \((3)\). \((9)\) was combined with \((3)\) in either of two phases shown on the abscissa: \(\Phi = 0\) (peaks-subtract), \(\bigcirc\), or \(\Phi = \pi\) (peaks-add), \(\blacktriangle\). The increase in log contrast threshold of \((9)\) following adaptation to a 21.6% contrast, 3 cpd square-wave grating \(\bigcirc\) on a 34% contrast, 3 cpd triangle-wave grating \(\blacktriangle\) is indicated on the ordinate. Error brackets denote \(\pm 1\) standard error.

Fig. 4. Effect of adaptation to either the fundamental or the third harmonic of a 21.6% contrast, 3 cpd square-wave grating. Filled circles \(\bullet\) and empty circles \(\bigcirc\) show the results of adaptation to the 27.6% contrast fundamental and the 9.1% contrast third harmonic, respectively. Axes are labeled as before.

observation interval in which there was no change in the display). For all four observers, more contrast was required to discriminate \((9)\) from a blank field than to discriminate \((3,9; \Phi)\) from \((3)\). Such facilitation of \((9)\) by \((3)\) has been previously reported.\(^7\) \(^{11}\) \(^{12}\) Two observers, S. M. and D. S., showed more facilitation for the \((3,9; 0)\) phase combination of \((9)\) and \((3)\); the other two observers showed the same amount of facilitation for both phase combinations.

Fig. 3 shows the increase in log contrast threshold of \((9)\) following adaptation to a 21.6% contrast square-wave (empty squares) or a 34% contrast triangle-wave (empty triangles) as a function of the phase in which \((9)\) and \((3)\) were combined to form \((3,9; \Phi)\). The filled squares and filled triangles on the abscissa represent \(\Phi = 0\) (peaks-subtract) and \(\Phi = \pi\) (peaks-add) phase combinations, respectively. For example, the leftmost empty square in Fig. 3 shows that following adaptation to the square-wave grating, log contrast threshold for \((9)\), based on discrimination of \((3,9; 0)\) from \((3)\), increased by about 0.3 log units for observer R. S. Each data point is based on at least 1.6 kilotrials. Error brackets represent \(\pm 1\) standard error.

The ability of an observer to discriminate \((3,9; 0)\) from \((3)\) was markedly affected by
adaptation to the square-wave, but not the triangle-wave, grating. Furthermore, the effects of the square-wave adapting grating were phase-specific. Following adaptation to the square-wave, all observers showed a significantly (p < 0.01) greater adaptation effect for the (3,9:0) vs. (3) discrimination. Φ = 0, of course, is the phase that (3) and (9) occupy in the 3 cpd square-wave grating. Phase-specific effects for the triangle-wave adapting grating were much smaller, if they existed at all. Following adaptation to the triangle-wave grating, only one observer, R. S., showed an adaptation effect for the (3,9:π) vs. (3) discrimination that was significantly greater (t = 3.57, p < 0.01) than the adaptation effect for the (3,9:0) vs. (3) discrimination.

Fig. 4 shows the effect of adapting to either the fundamental (filled circles) or third harmonic (empty circles) of the 21.6% contrast square-wave. The axes are labeled as before, and each data point is based on at least 1 kilotrial. Neither the square-wave's fundamental nor its third harmonic produced a significant phase-specific adaptation effect, although the third harmonic clearly did cause a small adaptation effect that was not phase-specific.

Fig. 5 shows the effect of adapting to the square-wave's fundamental and third harmonic combined in the peaks-subtract phase (i.e., (3,9:0)). The axes are labeled as before, and each data point is based on at least 1.6 kilotrials. This adaptation grating did not cause significant phase-specific adaptation although there was a clear tendency in that direction.

**Discussion**

Adaptation to a 3 cpd square-wave grating upset our observers' ability to discriminate (3,9:0) from (3) but did not affect their ability to discriminate (3,9:π) from (3). This result cannot be explained by assuming that observers discriminated (3,9:0) from (3) by exclusively monitoring independent narrow-band channels tuned (maximally sensitive) to 9 cpd. On the other hand, this result would be expected if observers discriminated (3,9:Φ) from (3) by monitoring activity in wide-band, phase-specific channels that also react to square-wave gratings whereas they used a different type of channel, relatively insensitive to square-wave gratings to discriminate (3,9:π) from (3). For ease of exposition we will use the term square-wave channel to refer to the hypothetical mechanism observers apparently used to discriminate (3,9:0) from (3) (with the understanding that a square-wave channel may turn out to be a collection of edge or some other type of channels).

The hypothesis that different channels are best stimulated by (3,9:0) and (3,9:π) is consistent with the perceptual correlates of these gratings. That is, the perceptual consequence of adding a near-threshold (9) to a moderate-contrast (3) depends on the phase of the combination; the light/dark bar bound-
aries of (3,9:0) appear sharper than those of (3), but (3,9:π) appears to have thin bars centered within the wider bars of its fundamental periodicity, 3 cpd. It is interesting to note that with (9) near threshold the light/dark boundaries in (3,9:π) appear less sharp than those of (3), although this perceptual characteristic is generally not as salient as the thin bars.

If different channels are used to detect the addition of (9) to (3) in the two phases, Φ = 0 and Φ = π, then sensitivity to the addition of (9) might depend on phase. In fact, Stromeyer and Klein have reported a slightly greater d' for (9) added to (3) in the Φ = 0 phase. Nachmias and Weber, however, failed to find any consistent differences in the detectability of the two phase combinations. Two of our observers show a consistently greater sensitivity to the Φ = 0 phase combination, but the other two observers are equally sensitive to both phases. All of this suggests that different channels are being used to detect the two phase combinations and that their sensitivities are roughly equal for some, but not all, observers.

Atkinson and Campbell have investigated the perceptual stability of gratings constructed from a number of different phase combinations of (3) and (9). The rate of perceptual fluctuation had relative minima at (3,9:0) and (3,9:π), with the (3,9:0) combination showing the greatest perceptual stability. The authors suggested a single "phase selective device" that responds to both of these phases and is responsible for perceptual stability. Although it is entirely possible that their proposed phase selective device, responsible for perceptual stability, has nothing to do with sensitivity to the addition of (9) to (3), our results allow a slightly different interpretation. Perhaps there are two different "devices," one of which responds best to (3,9:0) and the other to (3,9:π). When one device is clearly more active, perception is stable. As activity in the two devices becomes more nearly equal, however, perception tends to fluctuate—first dominated by one, then the other device. Since there are different devices most sensitive to (3,9:0) and (3,9:π), our phase-specific adaptation effect makes sense—the square-wave adapted one device more than the other.

Visual inspection of Fig. 4 gives the accurate impression that adaptation to (9) had a greater, but not phase-specific, effect than adapting to a (3) with three times the contrast (t = 3.77, p < 0.002; data pooled across phase and observers for each adaptation condition). Although we shall not go into details here, this result is consistent with a model assuming that narrow- and wide-band mechanisms operate in series, with input to the wide-band mechanisms first passing through a phase-selective gate.

We have suggested that observers discriminate (3,9:0) from (3) by monitoring activity in wide-band, phase-specific channels. The data shown in Figs. 3 and 5 can be used to obtain a rough idea of the minimum bandwidth of these square-wave channels. The results for all three observers in Fig. 5 are very similar. Pooling their data for the discrimination of (3,9:0) from (3) yields an average adaptation effect of 0.19 log units. Similar calculations on the data shown in Fig. 3 for the same three observers yields an average adaptation effect of 0.31 log units. The complete square-wave grating produced significantly greater (t = 3.38, p < 0.005) adaptation than its fundamental and third harmonic (i.e., (3,9:0)) used as an adapting grating. This means, of course, that the higher harmonics of the square-wave had a significant impact on the over-all adaptation effect. Assuming that the square-wave fundamental also made a significant contribution, the bandwidth of the square-wave channels must be at least 2 octaves.

Unlike the square-wave grating, the triangle-wave adapting grating did not create an easily demonstrable phase-specific adaptation effect. It is possible that the higher harmonic components of the triangle-wave were simply too small to cause a significant adaptation effect (the third harmonic component of the triangle-wave had a contrast of only 2.9%). This possibility is consistent with the observations that (1) all observers showed a tendency toward phase-specific adaptation
to the triangle-wave and (2) the one observer who did show phase-specific adaptation to the triangle-wave is also the observer who was most sensitive to the (3,9:π) addition of the (9).

In conclusion, our data clearly support the notion of wide-band, phase-specific channels sensitive to sharp edges. The minimum bandwidth of these channels is at least 2 octaves. Unfortunately, we are unable, as yet, to report the bandwidth of the device used to detect the Φ = π addition of (9) to (3).

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REFERENCES