# Appearance of the Frequency-Doubling Stimulus at Threshold

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**Purpose.** It has been argued that the threshold for detecting frequency-doubling (FD) technology perimeter stimuli differs from the threshold for perceiving spatial structure (pattern) in the same targets. Thresholds for perceiving spatial structure have typically been assessed using orientation-identification experiments. The authors investigated the influence of orientation, edge profile, and psychophysical method on the origin of the reported differences in detection and orientation-identification thresholds for FD gratings.

**Methods.** Detection and orientation-identification thresholds were determined in 12 observers with the use of FD stimuli (0.25 cyc/deg, 25 Hz) presented centrally and at 15° eccentricity. Edge profile (square- and Gaussian-windowed) and orientation (horizontal, vertical, and oblique) were independently modified. Detection thresholds were also measured for spatially uniform flickering targets (25 Hz). Orientation-identification thresholds using a two-alternative forced choice (2-AFC) and a two-interval forced choice (2-IFC) method were also compared in five experienced observers.

**Results.** Orientation-identification and detection thresholds did not significantly differ under any condition tested. Orientation-identification thresholds obtained with 2-AFC were not significantly different from those obtained with 2-IFC. Thresholds for spatially uniform flicker were significantly lower than for FD stimuli.

**Conclusions.** The authors found that orientation-identification and detection thresholds for FD gratings did not differ and argue that recent findings to the contrary arise from the inappropriate use of spatially uniform flicker targets as alternatives in 2-IFC experiments. (*Invest Ophthalmol Vis Sci.* 2009;50:1477–1482) DOI:10.1167/iovs.08-2866

Frequency doubling (FD) describes the doubling of the apparent spatial frequency of a low spatial-frequency grating when it is counterphase flickered at a rapid rate.[1] Maddess and Henry[2] showed that the minimum contrast required to detect this FD phenomenon was increased in subjects with glaucoma, prompting the development of the Frequency Doubling Technology (FDT) Perimeter (Humphrey FDT Perimeter; Carl Zeiss Meditec, Dublin, CA, and Welch Allyn, Skaneateles Falls, NY). For the purposes of this article, we will call low spatial-frequency gratings flickered at rapid rates FD stimuli, though this designation is based purely on the physical characteristics of the stimulus and, hence, does not necessarily mean that such gratings produce an altered spatial-frequency percept. Various studies have shown that the FDT Perimeter is a sensitive tool for detecting glaucoma,[3] and a more recent higher-spatial resolution version of the perimeter[4] appears to maintain this sensitivity.[5,6]

The FDT Perimeter does not require patients to explicitly detect the presence of spatial FD but simply the presence of any stimulus. In fact, it has been suggested that subjects be instructed to respond to any stimulus that flickers, shimmers, or is striped.[3] Indeed, if subjects are asked to respond only to the presence of spatial structure (stripes) in the stimuli, abnormally high thresholds can result in observers with otherwise normal vision.[7] One explanation for these abnormally high thresholds is that spatial structure is not visible in an FD stimulus at its detection threshold (the minimum contrast required to detect the presence of the stimulus) and that spatial structure—and, correspondingly, the FD percept—only becomes visible at stimulus contrasts above the detection threshold. Several studies have investigated whether spatial structure is perceived at detection threshold, but the evidence thus far has been contentious or inconclusive. Some studies have suggested that only amorphous flicker with no spatial structure is present at detection threshold (Bosworth CF, et al. *IOVS* 1999;40:ARVO Abstract 4436).[2,8] Others have shown that orientation-identification thresholds are similar to absolute detection threshold,[9–11] suggesting that spatial structure is visible at detection threshold.

The most recent studies addressing this issue have equally failed to reach a consensus. Quaid et al.[12] reported a significant difference of 0.1 log units between detection and orientation-identification thresholds, whereas Vallam and Metha[11] did not find such a difference. Given these discrepancies, it is worth examining each study's methodology in more detail. Quaid et al.[12] measured orientation-identification thresholds for vertically oriented gratings using a two-interval forced choice (2-IFC) technique in which the interval not to be detected contained either a flickering patch (0 cyc/deg) or a horizontal grating. This is of potential concern because the stimuli in the two intervals might not have been equally detectable, allowing the subject to perform the task based on the relative detectability of the stimuli in each interval rather than the perception of a vertically oriented grating per se. Detectability differences can arise from various causes, such as changes in grating orientation[13] and orientation-dependent (horizontal vs. vertical) display artifacts in cathode ray tube (CRT) monitors,[14] and because contrast sensitivity changes with spatial frequency,[13] though for the low spatial frequencies used in FD stimuli the latter is probably the most important cause. Vallam and Metha[11] avoided potential detectability artifacts by using a combined detection and orientation-discrimination task in a 2-IFC experiment in which the interval not to be detected was blank. Furthermore, they used gratings oriented obliquely (45° and 135°), for which detectability would presumably be equal and which would be subject to similar CRT artifacts. Their study used only four observers, however, and its power to detect a significant difference between detection and orientation-identification thresholds of the magnitude described by Quaid et al.[12] is unknown.

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Another difference between the two studies involves the window in which FD stimuli were presented. Although Quaid et al.[12] presented gratings in a square window, Vallam and Metha[11] used a smooth Gaussian window. The use of a hard-edged window can introduce artifacts[15] that might lower detection thresholds compared with orientation-identification thresholds, despite identical detection and orientation-identification thresholds for an unwindowed grating. That detection and orientation-identification thresholds for square-windowed stimuli are equally affected by defocus[16] suggests that such artifacts may not be important, though this is yet to be explicitly demonstrated.

A final difference that occurs between various frequency-doubling studies concerns the type of forced choice methodology used, in particular whether the two alternatives to be discriminated are represented as separated in space or in time (2-IFC). Demands on attention and memory are not identical in each task type, and it has been demonstrated that differences in measured threshold can occur between these two types of methodology.[17] A further complication arises with the orientation-identification often performed in FD experiments,[9,10] which differs from conventional two-alternative forced choice (2-AFC) by having only one alternative presented (tilted left or tilted right) in a single location on any given trial. The influence of such methodological differences between various studies is unclear.

In this study we determined detection and orientation-identification thresholds for FD stimuli with a sample size appropriate to find a difference equivalent to that described by Quaid et al.[12] Importantly, we also measured detection thresholds for horizontal flickering gratings, vertical flickering gratings, and flickering patches to determine whether the forced-choice method of Quaid et al.[12] might have been compromised by detectability differences between the stimuli used. In addition, we assessed the influence of square- versus Gaussian-windowed stimuli to determine whether any differences in detection and orientation-identification thresholds might be the result of stimulus artifacts. Finally, we investigated the influence of test methodology (2-AFC vs. 2-IFC) on thresholds for detecting the spatial structure in FD stimuli.

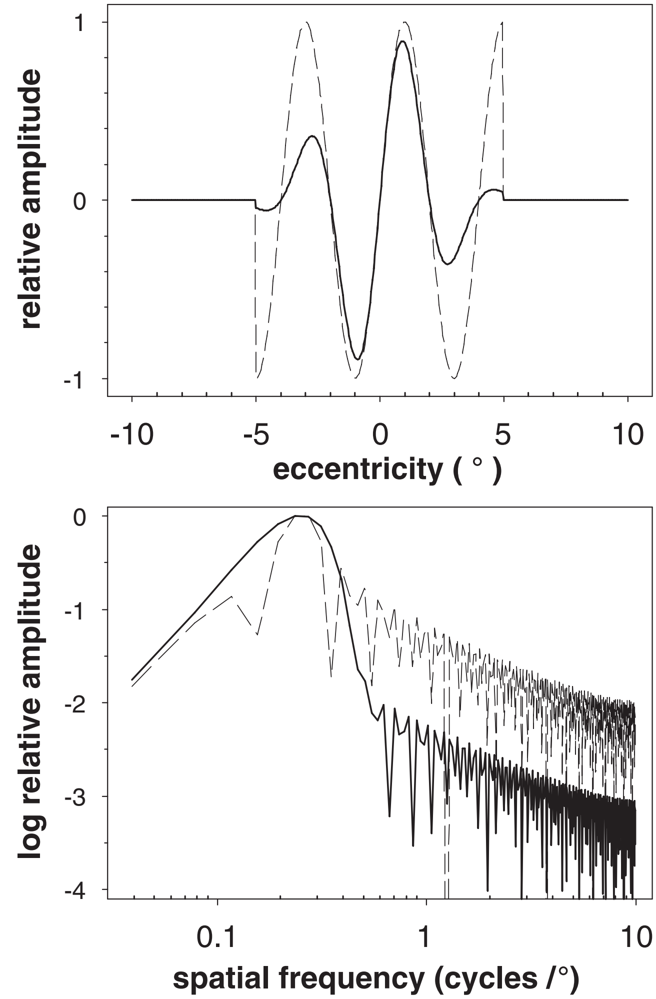


**Figure 1.** Cross-sectional spatial waveforms (*top*) and fast Fourier transform (FFT; *bottom*) of the waveforms for the square-windowed and Gaussian-windowed sine wave gratings (*dashed thin lines* and *solid thick lines,* respectively). The FFT was performed with commercial software (MATLAB; The MathWorks) using a 0.05° sample width, and the amplitude spectra were normalized to have a maximum power of 1 (log relative amplitude 0). In absolute terms, the maximum of the amplitude spectrum for the square-windowed waveform was 0.3 log units higher than for the Gaussian-windowed waveform.

## Methods

### Apparatus and Procedure

We presented stimuli on a calibrated gamma-corrected video monitor system (Visage graphics card [Cambridge Research Systems, Kent, UK]; Diamond Pro 2070SB monitor [Mitsubishi, Tokyo, Japan]) with a frame rate of 100 Hz. The monitor resolution was 800 × 600 pixels (width by height) and subtended 43° by 33° at the 50-cm viewing distance. Ambient room illumination was dim, and the background luminance of the monitor was 45 cd/m$^2$ (CIE 1931: $x = 0.279$, $y = 0.299$). A chin rest restrained the subject's head. Subjects viewed the monitor binocularly using their habitual refractive correction.

We used two general stimulus types, FD stimuli (0.25 cyc/deg sinusoidal grating, flickered at 25 Hz) and a spatially uniform flicker stimulus (0 cyc/deg grating, flickered at 25 Hz). All flicker was presented in counterphase with a sinusoidal temporal waveform. Although our sinusoidal temporal waveform differed from the square temporal waveform used in the FDT Perimeter, it is well established that psychophysical flicker thresholds are insensitive to temporal waveform from approximately 10 Hz and greater.[18,19] This is also consistent with electrophysiologically recorded responses from macaque retinal ganglion cells projecting to the magnocellular pathway, which are dominated by the fundamental of a temporal waveform by 20 Hz and greater.[19]

Stimuli were presented in either a 10° × 10° square window or a Gaussian envelope (SD, 2°) truncated by the same square window (Fig. 1, upper panel). Stimulus contrast was linearly ramped up to the test contrast over 160 ms, remained at the test contrast for 400 ms, and was linearly ramped down to zero over 160 ms. The interstimulus interval (ISI) was 280 ms. The spatial phase of grating stimuli was set to give a zero-crossing at the center of the window so as to avoid any artifacts caused by a noninteger number of cycles within the window.[16]

For all experiments we measured thresholds, in logarithmic units, according to a 30-presentation forced choice ZEST (Zippy Estimation by Sequential Testing) procedure with auditory feedback regarding the correctness of each response. Subjects responded by means of a button-press.

### Subjects

Twelve healthy subjects (mean age, 31.7 ± 6.9 [SD] years) participated in experiment 1, and a subset of five subjects performed experiment 2. All subjects were experienced at performing psychophysical observations and had normal visual fields as determined by the screening program (C-20–1 test) of the FDT Perimeter (Humphrey Systems; Welch Allyn). A minimum sample size for experiment 1 was determined by a paired *t*-test power calculation (Lenth RV [2006]; Java

Applets for Power and Sample Size [Computer software]. http://www.stat.uiowa.edu/~rlenth/Power), by which a sample size of 10 subjects results in a power of 80% for detecting the 0.1 log difference between detection thresholds and orientation-identification thresholds reported by Quaid et al.[12] We assumed the SD of the difference in measurements to be 0.07 (estimated from pilot data from six subjects). All participants provided informed written consent, and all procedures were carried out in accordance with the tenets of the Declaration of Helsinki and were approved by our institutional ethics committee. Data collection involved two visits within 1 week, with the ordering of tests counterbalanced. Each visit involved a period of training to ensure subjects fully understood the tests.

### Experiment 1: Orientation-Identification versus Detection Thresholds

In this experiment we measured detection thresholds for various stimuli and orientation-identification thresholds. We used a 2-IFC procedure to measure detection thresholds, in which the interval not to be detected was blank. Orientation-identification thresholds were measured using a two-alternative forced choice (2-AFC) procedure with a single interval in which subjects had to determine the orientation (tilted 45° or 135°) of the grating. The beginning of each interval was signaled by an auditory tone.

With the use of square-windowed stimuli, we measured detection thresholds for spatially uniform flicker and FD gratings oriented horizontally, vertically, or diagonally (45° and 135° randomly interleaved). For Gaussian-windowed stimuli, we measured detection thresholds for diagonal gratings only. Stimuli were presented centrally or at 15° nasal eccentricity, and two interleaved estimates of threshold per location were obtained in each run of approximately 5 minutes duration. The final threshold estimate was taken as the arithmetic mean of the individual estimates for a particular location (average of four estimates). Only one type of stimulus or task type (detection or orientation identification) was used per run.

### Experiment 2: Comparison of 2-IFC and 2-AFC Methodologies

In experiment 2, we investigated the influence of the type of forced-choice methodology used to determine orientation identification thresholds. For the 2-AFC methodology, we measured thresholds as outlined in experiment 1. For the 2-IFC methodology, we presented a grating at 45° in one randomly selected interval and at 135° in the other interval and asked subjects to select in which interval the grating orientation was 45°. All stimuli were Gaussian windowed and were presented centrally or at 15° nasal eccentricity. Two threshold estimates at each location were obtained per run, with subjects performing 12 runs for each paradigm in an interleaved and counterbalanced fashion. Average thresholds were therefore obtained from 24 threshold estimates per location.

### Statistical Analysis

In experiment 1, we performed a general linear model two-way repeated-measures (RM) ANOVA (SPSS 16.0; SPSS Inc., Chicago, IL) for the square-windowed data with two within-subjects factors. One was condition (orientation-identification with four detection conditions: horizontal, vertical, oblique, spatially uniform flicker), and the other was test location (central, peripheral). Gaussian stimuli were analyzed separately with a similar RM ANOVA, differing only in the condition (orientation-identification, detection) within-subjects factor. If overall significant differences were found, we performed post hoc testing with a one-way RM ANOVA and a Dunnett's test using the orientation-identification conditions as the reference condition (Prism 4.0; GraphPad Software, La Jolla, CA). In experiment 2 we used a general linear model two-way RM ANOVA with two within-subject factors, test location (central, peripheral) and test method (2-AFC, 2-IFC).

## Results

### Experiment 1: Orientation Identification versus Detection Thresholds

Figure 2 shows the mean threshold values for the conditions investigated. Considering the square-widowed stimuli first (left panels), two-way RM ANOVA found a significant difference between conditions [$F(4,44) = 25.92$; $P < 0.001$] but no effect of eccentricity [$F(1,11) = 3.42$; $P = 0.091$] or any interaction between the two [$F(4,44) = 1.32$; $P = 0.279$]. One-way RM ANOVA and Dunnett's multiple comparison post hoc test found that the spatially uniform flickering stimulus was significantly different from the orientation-identification control ($P < 0.010$). All other comparisons were not significant. For the Gaussian-windowed stimuli, the two-way RM ANOVA found no significant difference between detection and orientation thresholds [$F(1,11) = 4.52$; $P = 0.057$], though the effect of eccentricity was significant [$F(1,11) = 9.87$, $P < 0.009$]; there was no interaction between these two factors [$F(1,11) = 0.05$, $P = 0.830$].

### Experiment 2: Comparison of 2-IFC and 2-AFC Methodologies

Figure 3 shows the results for the orientation-identification thresholds measured with 2-IFC and 2-AFC methodologies (filled and unfilled symbols, respectively). There was no significant effect of test method [$F(1,4) = 0.77$; $P = 0.430$] or test location [$F(1,4) = 6.12$; $P = 0.069$], and there was no significant interaction between the two [$F(1,4)= 0.17$; $P = 0.699$].

## Discussion

The primary aim of this study was to investigate claims that significant differences existed between detection and orientation-identification thresholds for FD stimuli. In doing so, we found no significant differences, consistent with previous findings[9–11,20] in healthy subjects. Our results do, however, contrast with the 0.1 log unit difference reported by Quaid et al.,[12] despite a study design meant specifically to detect such a difference. We found no significant effect of eccentricity on the relationship between detection and orientation-identification thresholds (Fig. 2).

When measuring pattern detection thresholds with the 2-IFC task, Quaid et al.[12] used a vertical FD stimulus in one interval and a spatially uniform flickering patch in the other. We found that detection thresholds for a flickering patch were significantly lower than for an FD stimulus (Fig. 2). Therefore, these two stimuli should not be used as alternatives in a conventional 2-IFC experiment, especially if they are presented at identical physical contrasts. If they are, an observer attempting to maximize his or her performance on the task should simply respond to the least visible interval, thereby resulting in a flicker detection threshold rather than an orientation-identification threshold. This threshold would be significantly lower than FD detection thresholds. It is curious that Quaid et al.[12] found the opposite of this when using flickering and FD stimuli in a 2-IFC task, that is, that FD orientation-detection thresholds were increased compared with FD detection thresholds. It therefore appears that their subjects adopted a suboptimal strategy for performing the task, possibly to ignore the artifact present in their methodology. The influence of subject criteria on such a suboptimal strategy is unknown. Although our testing was performed at a slightly lower luminance than that used by Quaid et al.[12] (45 vs. 50 cd/m$^2$, or 0.05 log units), this would not be expected to alter the log difference between detection thresholds for FD stimuli and patches of uniform flicker given that both are subject to approximately linear light adaptation.[21]

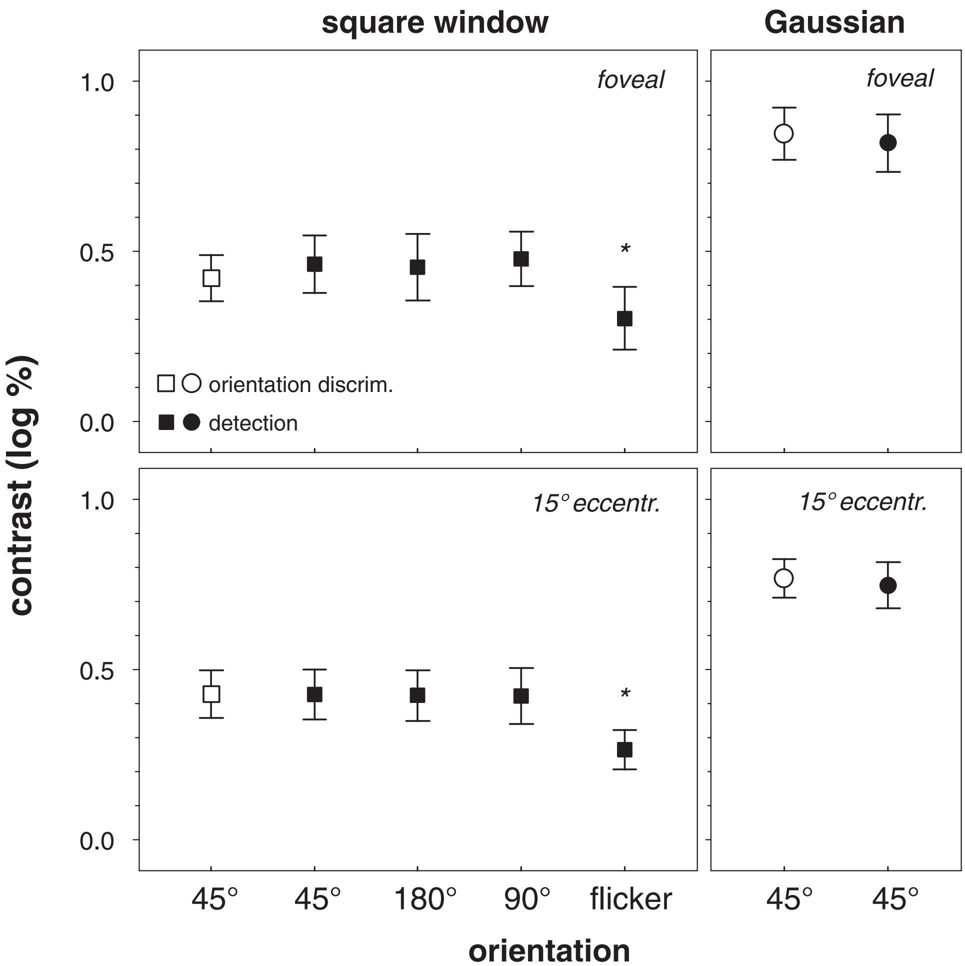


**Figure 2.** Mean threshold values (±SEM) for each stimulus in experiment 1 for foveal and eccentric locations (*top* and *bottom*, respectively). *Unfilled symbols*: orientation-identification thresholds. *Filled symbols*: detection thresholds. Obliquely oriented gratings are labeled 45°, though in the experiment they appeared at 45° and 135° with equal probability. *Asterisks*: conditions that differed significantly from orientation-identification thresholds (*unfilled symbols*) with one-way repeated measures ANOVA run separately for each panel.

We found that horizontal and vertical gratings had similar detectability (Fig. 2) and hence might be appropriately used as alternatives in a 2-IFC orientation-detection experiment. Quaid et al.[12] used such targets but again found that orientation-identification thresholds were elevated compared with detection thresholds, in contrast to the results presented here and to those of Vallam and Metha.[11] However, given that the subjects in the Quaid et al.[12] study appear to have adopted a suboptimal strategy that elevated orientation-detection thresholds when a spatially uniform flicker stimulus was used as an alternative, it is not unreasonable to assume that the same subjects adopted a similar strategy when other stimuli were used as alternatives.

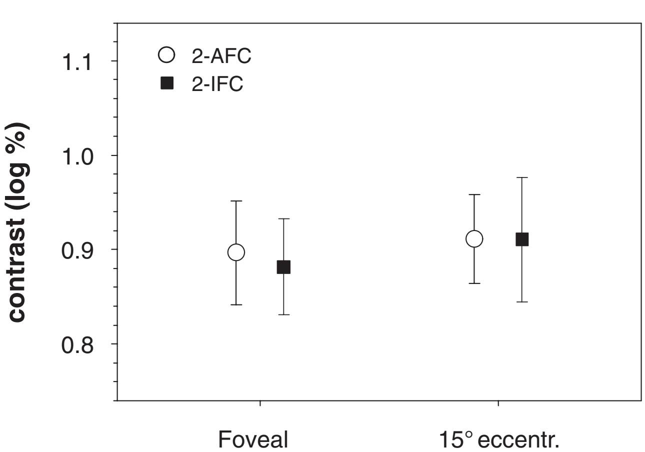


**Figure 3.** Orientation-identification thresholds obtained using 2-AFC and 2-IFC testing paradigms. Data points give mean (±SEM) thresholds averaged from five observers. Absolute differences between experimental methodologies were 0.015 and 0.001 log units (foveal and 15° eccentric, respectively).

## Mechanisms Underlying the Frequency-Doubling Phenomenon

The mechanisms underlying the FD phenomenon are the subject of debate. Maddess and Henry[2] originally suggested that the phenomenon arose from a subpopulation of magnocellular cells within the retina with nonlinear spatial responses ($M_Y$ cells), though a more recent physiological study[22] has failed to find evidence for such cells in primates and has argued that nonlinear spatial responses cannot generate an FD effect. Evidence also shows that FD targets are detected by the same mechanisms as those that detect spatially uniform flicker.[9] Although our study was not designed to address what mechanisms underlie the FD phenomenon, it should be noted that the significant differences between detection thresholds for FD stimuli and spatially uniform flicker found in our study (Fig. 2) do not provide evidence for separate mechanisms being involved in detecting these two stimulus types. Rather, such differences likely reflect the operation of a single mechanism showing low-pass spatial tuning and so are in agreement with previous work.[9]

## Effect of Stimulus Window

Most studies investigating FD stimuli have used targets presented in a hard-edged window.[8–10,22,23] Such windowing can produce significant artifacts at spatial frequencies away from the nominal spatial frequency of the grating stimulus, as demonstrated in Figure 1. Our use of a Gaussian-windowed stimulus reduced the magnitude of these high spatial-frequency artifacts by approximately 1 log unit (Fig. 1). Despite differences in high spatial-frequency artifacts, we found the relationship between orientation-identification and detection thresholds was identical when hard-edged or Gaussian-windowed targets were used (Fig. 2). That optical defocus affects detection and orientation-discrimination thresholds equally for small and large FD targets[16] suggests our findings regarding edge profile generalizes to the smaller low spatial-frequency FD targets used in the new-generation Humphrey Matrix Perimeter.[4] Targets of the sort used in the Humphrey Matrix are influenced by edge effects in a spatial-phase–dependent manner, however,[25] and so orientation-discrimination thresholds would have to be subject to the same edge effects for the relationship between detection and orientation-discrimination thresholds to remain unaffected by edge profile.

## Effect of Experimental Methodology

We found no significant difference between orientation-discrimination thresholds when using an orientation-discrimination paradigm, as described in experiment 1, or a 2-IFC method similar to that of Quaid et al.[12] Previous work has shown that a temporal 2-IFC produced lower thresholds than a conventional spatial 2-AFC,[17] with an average difference of 0.08 log units (four observers) found between the two methods for isolated Gabor targets (4 cyc/deg, at locations separated by 8° in the 2-AFC). Should such a difference have been preserved in the 2-AFC task in our orientation-discrimination paradigm, it would have suggested that orientation-identification thresholds should be, if anything, lower than those found in previous studies. Therefore, the type of forced-choice methodology could not be used as an explanation of why a difference between absolute and orientation-discrimination thresholds was not found in these studies. As noted by García-Pérez et al.,[17] the spatial and temporal forced-choice psychophysical tasks place different demands on an observer's attention and memory and are differentially affected by inhomogeneities either in the observer's visual field or in the stimulus display. The role of attention in the simultaneous-judgment task used by Vallam and Metha[11] is also difficult to quantify.[25] Nevertheless, we did not find a difference between the thresholds obtained with two forced-choice methodologies previously used in FD investigations, and previously described differences[17] are in the incorrect direction to explain discrepancies between previous FD studies. It should be noted, however, that clear changes in threshold can result if methodologies are incorrectly implemented, as we argue is the case in certain experiments reported by Quaid et al.[12]

## Implications for Frequency-Doubling Technology Perimetry

Despite potentially conflicting results regarding whether frequency doubling is perceived at detection thresholds, a number of clear conclusions emerge from the literature regarding the use of FD gratings in perimetry. First, evidence indicates that detection and orientation-identification tasks isolate the same mechanism or mechanisms in healthy observers.[9] Therefore, asking healthy subjects to respond to any stimulus in the FDT Perimeter will isolate the same mechanism that is isolated when subjects are asked only to respond to spatial form, even if absolute threshold values differ between these two tasks. Second, the relationship between detection and orientation-identification thresholds remains constant regardless of age or the presence of visual field loss from glaucoma,[10] indicating that detection thresholds continue to isolate the same mechanism as orientation-identification thresholds even in the presence of visual field loss. This conclusion holds despite the small methodological differences between the detection and orientation-identification tasks used by McKendrick et al.[10] It is possible that orientation-identification thresholds do not, in fact, represent thresholds for the FD percept and that a criterion based explicitly on doubling would isolate a different mechanism. Most subjects see FD gratings as close to doubled at orientation-identification thresholds, however,[11] and this is equally true in areas of visual field damaged by glaucoma,[10] consistent with the idea that perceived spatial frequency does not change as a function of suprathreshold contrast level.[11] Finally, many clinical trials have found the FDT Perimeter is a useful tool for detecting glaucoma[3]; presumably, most of these have used a detection criterion. Therefore, despite debate regarding the coincidence of detection and FD percept thresholds, there is good evidence that the detection criterion used in FDT perimetry isolates the same mechanisms as those originally investigated by Maddess and Henry.[2]

In summary, our findings suggest that orientation-identification and detection thresholds for FD stimuli do not differ significantly and that recent results to the contrary may be the result of methodological problems. Our results indicate that results can be confidently compared between studies requiring the detection of spatial form in FD stimuli and studies using the clinical method wherein subjects responds to any stimulus.

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