1. INTRODUCTION
Many studies have shown that contrast sensitivity under photopic conditions declines with age (see Refs. 1–4 for reviews), but the relative contributions of optical and neural factors to this age-related reduction in sensitivity are still debated (cf. Refs. 5–8). To address this issue, we adopted the technique of measuring detection thresholds for sine wave gratings embedded in different levels of external Gaussian noise. This technique is useful, because it can be used to parcel the various factors that affect contrast sensitivity into two separate components: equivalent noise and calculation efficiency. The primary aim of the current paper is to examine whether changes in one or both of these components underlie age-related changes in contrast sensitivity. Detailed descriptions of the theoretical assumptions that underlie calculations of equivalent noise and efficiency are provided by several authors,9–14 so only the key points are discussed here.

A. General Framework
The general framework that we adopted for analyzing age-related changes in visual sensitivity is a variant of ideal observer theory. Consider a typical two-alternative forced-choice (2AFC) detection task in which an observer must decide whether a stimulus was presented on the left-hand side or right-hand side of a display (or in the first or second interval for a two-interval forced-choice task). For the case of a signal specified exactly, an ideal strategy is to use a linear filter, or template, that is matched to the spatial and temporal characteristics of the stimulus. The filter’s response is calculated at both possible locations, and the one that yields the largest response is selected. If the performance-limiting noise is Gaussian, and if a stimulus appears at each location with equal probability, then this strategy will maximize the percentage of correct responses.

Of course, many factors conspire to make human performance worse than ideal. For example, the optics of the human eye degrade the stimulus. Neural mechanisms might further attenuate the stimulus and introduce noise. In addition, human observers might encode the stimulus with filters that are not matched precisely to its spatial and/or temporal properties or use suboptimal decision rules or use a decision criterion that fluctuates randomly across trials. All of these factors undoubtedly contribute in varying degrees to relatively poor performance in real observers. One way of differentiating the effects of these factors is to measure detection thresholds for targets embedded in different levels of external noise added to the stimulus on the display. Several hypothetical threshold versus noise curves are shown in Fig. 1. For a quantum-limited observer (Fig. 1, curve A), thresholds (expressed in terms of contrast energy) are proportional to noise level and the threshold versus noise curve intercepts the abscissa at the origin.15 Several studies have shown that detection thresholds for real observers are also proportional to the external noise level9,13,16 but the threshold versus noise functions from real observers have steeper slopes than the ideal function. Also, functions from real observers intercept the abscissa at more negative values than the ideal function (Fig. 1, curve D).

A simple model for analyzing these threshold versus noise functions is illustrated in Fig. 2 (Refs. 10–12). This black-box model of a real observer differs from an ideal observer in two ways. First, a constant, contrast-invariant noise \( N_v \) is added to the external stimulus. Second, a suboptimal, contrast-invariant calculation is performed on the input. This calculation can be thought of as the application of a linear filter, or receptive field, that reduces the input to a single number (i.e., the filter’s response) that is then used to make a decision regarding the presence or absence of the target. This model parcels all the factors that contribute to suboptimal human performance into two parts: one part that has a constant effect across levels of external noise and another part that has an effect that increases with increasing noise. To il-

Contrast sensitivity under photopic conditions declines with age; however, the cause of this decline remains unknown. To address this issue, we measured detection thresholds for sine wave gratings in noise, under various conditions of spatial-frequency uncertainty, and estimated observers’ internal noise and calculation efficiency. Statistical analyses revealed that efficiencies were lower for old (median age at 68 years) than for young (median age at 22 years) observers; no significant differences in internal noise were found. A control experiment ruled out the possibility that reduced retinal illuminance causes the decline in efficiency with age. Our results demonstrate that age-related neural changes play a major role in the decline in contrast sensitivity with age. Possible contributing mechanisms are considered. © 1999 Optical Society of America
in which real observers use a suboptimal calculation. For example, observers might base their decision on the response of a filter whose bandwidth is broader than the bandwidth of the stimulus. When the level of external noise is low, the amount of noise passed by the filter is low, and so performance is not changed significantly relative to ideal performance. However, as the level of external noise increases, more noise is passed by the filter and, consequently, performance becomes progressively worse relative to ideal performance. Hence a mismatch of stimulus and filter bandwidth increases the slope of the threshold versus noise function (Fig. 1, curve C). We use Pelli’s term, calculation efficiency, to refer to the reciprocal of the slope of the threshold versus noise function. With real observers, calculation efficiency is less than 1 and equivalent noise is greater than 0, thus yielding detection versus noise curves like the one illustrated in Fig. 1, curve D.

The model shown in Fig. 2 attributes lateral shifts in threshold versus noise functions entirely to changes in internal noise and all changes in the slope (i.e., calculation efficiency) to changes in the contrast-invariant calculation. Thus the model predicts that detection thresholds should follow the form

\[ E = \left( \frac{d'}{J} \right) (N + N_i), \]

where \( E \) is the contrast energy of the stimulus, \( d' \) is the criterion level of detectability at threshold, \( J \) is the calculation efficiency, and \( N \) and \( N_i \) are the two-sided spectral densities of the external and internal noises, respectively. \( N_i \) is zero and \( J \) is 1 for a quantum-limited observer, and therefore the threshold signal energy for an ideal observer equals \( d'^2 N \). It should be emphasized that both internal noise and calculation efficiency probably reflect the operation of several mechanisms. For example, optical blur, which reduces the amplitude of the signal and the external noise, but which does not alter the signal-to-external noise ratio, raises threshold by an amount that is independent of the level of external noise. Therefore, within the context of the model shown in Fig. 2, differences in optical blur are interpreted as changes in internal noise. Likewise, noise added to the stimulus by some neural mechanism, and random fluctuations of the decision criterion across trials, also changes performance in a manner consistent with changes in internal noise, provided that the neural noise and criterion fluctuations are constant across the levels of the external noise. However, a multiplicative neural noise whose variance increases with the level of the input would degrade performance more at high levels of external noise than at low levels and so would produce a change in calculation efficiency. A reduction in efficiency can also be caused by a mismatch between the bandwidth of the stimulus and filter. Thus measurements of threshold versus noise functions provide estimates of how two classes of mechanisms (i.e., those that change equivalent noise versus those that change calculation efficiency) affect performance but not of the relative effects of mechanisms within each class.
2. METHODS

A. Subjects

Twenty-four young (17–31 years old; median age at 22 years) and 24 elderly (60–83 years old; median age at 68 years) observers were paid to participate in the main experiment. A second, different group of twenty young (18–26 years old; median age at 21) observers participated in a low-luminance control experiment.

Young observers were students at the University of Toronto. Elderly observers were recruited through advertisements placed in local newspapers. All observers reported having normal or corrected-to-normal vision. In addition, all old observers reported that they underwent an ophthalmological exam during the year previous to testing. Observers with known ocular disease were excluded from the sample.

B. Apparatus and Stimuli

Stimuli were constructed on a Macintosh IIfx computer and displayed on a SuperMac 21-in. Platinum monitor (model STD-9760). Display size was 1152 × 870 pixels, which subtended a visual angle of 12.5 × 9.5 deg from the viewing distance of 171 cm. The spatial sampling rate was 77 pixels in.−1 (30.3 pixels cm−1), and the frame rate was 75 Hz, noninterlaced. The display had a neutral hue and an average luminance of 80 cd m−2. Luminance resolution was 8 bits/pixel, and the relation between a pixel’s value and display luminance was linearized in the software. The entire 8-bit range of the display produced a Michelson contrast of 90%.20

The stimuli were horizontal sine wave gratings embedded in one-dimensional horizontal Gaussian noise and were created in a 320 × 320 pixel array. Contrast at pixel (x, y) was defined as

\[ c(x, y) = \frac{L(x, y) - L_o}{L_a}, \]

where \( L(x, y) \) is the luminance at \((x, y)\) and \( L_o \) is the average luminance. The stimulus contrast function was

\[ c(x, y) = \alpha \cos(2\pi f y - \Phi) + G(y, \sigma), \]

where \( \alpha \) is Michelson contrast, \( f \) is spatial frequency in c/deg, \( \Phi \) is phase angle in radians, and \( G(y, \sigma) \) is a Gaussian random variable with a mean of zero and a standard deviation of \( \sigma \). The spatial frequency of the target was 1, 3, or 9 c/deg, and phase varied from 0 to 2\pi rad across trials. A different value of Gaussian noise was added to each row in the stimulus matrix. Noise standard deviations of 0.04 and 0.16 were used in the low- and high-noise conditions, respectively. The noise was generated with the algorithm described by Press et al.21 and tests indicated that the noise spectral density was flat in the neighborhoods around the test frequencies. Legge et al.9 showed that the spectral density of one-dimensional Gaussian noise is equal to the noise variance times the width of a single noise sample (i.e., one pixel). Noise spectral density \( N \), in the low- and high-noise conditions, was 1.75 × 10−5 deg and 2.83 × 10−4 deg, respectively.

On each trial, two patterns were presented simultaneously in the lower-left-hand and lower-right-hand portions of the display. The patterns were presented within circular apertures (diameter at 3.5 deg) that had the same average luminance and chromaticity as the rest of the display. The center-to-center separation between the stimuli was 6.25 deg. One stimulus contained a sine wave embedded in noise; the other contained only noise (i.e., the contrast of the sine wave was set to zero). To reduce age differences in memory for the target stimulus, a suprathreshold version (contrast at 0.25) of the target grating was shown without noise in the top half of the display. In the no-uncertainty condition (described below) the suprathreshold cue had the same spatial frequency as the target grating. In the frequency-uncertainty condition (described below) suprathreshold versions of the 1, 3, and 9 c/deg gratings were all displayed on each trial. All cues were presented within circular apertures (diameter at 3.5 deg). In the no-uncertainty condition the single cue was centered horizontally within the display, and in the frequency-uncertainty condition the other two cues
were centered 4.16 deg away on either side. It is important to note that the phases of the target and cue(s) were randomized independently on each trial, and therefore the cue(s) served to reduce only frequency uncertainty, not phase uncertainty.

C. Procedure
Grating detection thresholds were measured with a spatial 2AFC procedure. The observer’s task was to determine which of the two lower stimulus patches contained the target grating. Observers responded by pressing a key on a computer keyboard. The patterns remained visible until a response was made, and auditory feedback after each trial indicated whether the response was correct.

Viewing was binocular through natural pupils, and head position was stabilized with chin/forehead rests. Observers wore their normal optical correction for the viewing distance during testing. Eye movements were not monitored, and observers were told that they were free to inspect the stimuli any way they pleased. The monitor was the only source of illumination in the testing room.

Prior to the experimental session, observers were familiarized with the stimuli, display, and procedure. After a verbal description of the experiment, observers were shown a stimulus display from the frequency-uncertainty condition and each frequency in the no-uncertainty condition (see below). While the observer viewed each display from the experimental viewing distance of 171 cm, the experimenter pointed out that one stimulus contained only noise and the other contained a grating embedded in noise. In addition, the experimenter illustrated how the cue(s) could be used as a reminder of what the target(s) looked liked. The observers were told that the target’s contrast would be varied during the experiment and therefore that on some trials it would be difficult to decide which patch of noise contained the target. Finally, it was stressed that the observer should examine both patches of noise before making a response. The observer was given 12 practice trials, identical to those used in the experiment, for each display.

Each block of experimental trials was preceded by an additional 12 practice trials. On the first practice trial the contrast of the target grating was set randomly to a suprathreshold value between 0.22 and 0.28. During practice trials, grating contrast was decremented after every correct response and incremented after every incorrect response with a step size of 0.1 log unit for the first eight trials and 0.05 log unit for the final four trials. After 12 practice trials, the QUEST staircase procedure was used to manipulate grating contrast for 45 experimental trials. A maximum-likelihood procedure was used to fit a Weibull function to the data from the experimental trials, and threshold was defined as the 81% correct point on the psychometric function, which corresponds to a d’ of 1.2. A staircase was considered valid if the estimated threshold fell within the range of contrasts actually presented to the observer; otherwise, the data were discarded. For the purposes of statistical analysis, thresholds were converted into units of contrast energy according to the formula

\[ E = D \frac{c^2}{4}, \]

where \( E \) is energy, \( D \) is stimulus diameter in degrees, and \( c \) is contrast. Note that contrast energy and noise spectral density are expressed in the same units.

Thresholds were measured in two conditions. In the no-uncertainty condition, only one spatial frequency, identical to that of the cue presented on each trial, was shown in a block of experimental trials. At the end of a block, a new frequency was selected and the sequence of practice and experimental trials was repeated. Observers were allowed a brief rest in-between blocks. In the frequency-uncertainty condition, three QUEST staircases, one for each spatial frequency, were randomly intermixed, bringing the total number of experimental trials to 135. Observers were allowed a brief rest after completing 45 and 90 experimental trials. Three cues, one corresponding to each target frequency, were displayed on each trial.

Young observers were able to complete all 12 conditions in one session that lasted approximately 90 min. Most old observers required two experimental sessions scheduled within 1 week of each other.

D. Experimental Design
Age (young versus old) was a between-observers classification factor. Noise level (low versus high), target spatial frequency (1, 3, or 9 c/deg), and spatial-frequency uncertainty (no uncertainty versus frequency uncertainty) were within-observer variables. The orders of presentation of both the levels of external noise and frequency uncertainty were counterbalanced across observers. The order of presentation of spatial frequency in the no-uncertainty condition was randomized for each observer.

E. Low-Luminance Control Experiment
A control experiment was conducted to examine the effects of reduced retinal illuminance on detection thresholds. The stimuli and apparatus were identical to those used in the main experiment, with one exception: Observers viewed the stimuli through binocular neutral density filters that reduced luminance from 80 to 1.6 cd m\(^{-2}\). The procedure was also the same as in the main experiment, except that observers were tested only in the no-uncertainty condition.

3. RESULTS
Statistical analyses were performed with Systat (Macintosh version 5.2.1). Unless noted otherwise, interpretations of two- and three-way interactions were based on analyses of simple main effects and simple interaction effects.

A. Detection Thresholds
Detection thresholds, expressed in terms of contrast energy, are plotted against spatial frequency in Fig. 3. In each uncertainty condition, thresholds in both age groups generally increased with increasing spatial frequency and level of external noise. In the high-noise conditions, old observers had thresholds that were slightly greater than
those of young observers, and the age difference was nearly constant across spatial frequencies: The average threshold difference was 0.16 and 0.22 log unit in the no-uncertainty condition [Fig. 3(a)] and the frequency-uncertainty conditions [Fig. 3(b)], respectively. Age differences in the low-noise condition were more dependent on spatial frequency: Thresholds for 1 and 3 c/deg gratings were nearly identical across age groups, but thresholds for the 9 c/deg grating were 0.32 and 0.20 log unit higher in old observers in the no-uncertainty and the frequency-uncertainty conditions, respectively.

The effect of spatial-frequency uncertainty is plotted in Fig. 4. On average, increasing uncertainty raised thresholds by 0.22 and 0.30 log unit in the low- and high-noise conditions, respectively. Uncertainty effects generally were larger in old observers, but the age differences were small. Finally, in the high-noise condition the effect of uncertainty was similar across spatial frequencies, whereas in the low-noise condition the effect was slightly greater at 1 c/deg. We did not observe the strong dependence of the effect of uncertainty on target frequency reported by Hübner.

These observations were evaluated further in a 2 (age group) × 2 (uncertainty) × 2 (noise level) × 3 (spatial frequency) repeated-measures analysis of variance (ANOVA). Observers with missing data were dropped from the analysis, leaving a total of 16 observers in the elderly group and 22 observers in the young group. Of the eight old observers who failed to complete all conditions, four had a staircase in one condition that did not converge to a valid threshold and four did not return for the second experimental session and therefore were not tested in all conditions. Two young observers were removed from the analysis, because a staircase in one condition did not converge to a valid threshold. It is important to note that the observers included in the ANOVA
were representative of the entire sample, the means and standard deviations for those observers being essentially identical to the ones shown in Fig. 3.

The ANOVA was performed on log-transformed data to stabilize the variance across conditions, but similar results were obtained with the raw scores. The between-observers effect of age group, \( F(1,36) = 11.1, \ p < 0.002 \), and the within-observers effects of noise, \( F(1,36) = 2156.5, \ p < 0.001 \), and frequency \( F(2,72) = 143.7, \ p < 0.001 \), were significant. Increasing the level of external noise elevated thresholds more in old observers than in young ones, as indicated by a significant noise \( \times \) age group interaction, \( F(1,36) = 6, \ p < 0.02 \), and this age difference depended on the spatial frequency of the target, as shown by a significant noise \( \times \) frequency \( \times \) age group interaction, \( F(2,72) = 3.3, \ p < 0.04 \). The three-way interaction reflected the fact that the effect of the noise was similar in both age groups when the target was 9 c/deg but was greater for old observers with 1 and 3 c/deg targets. Finally, the within-observers effect of uncertainty was significant, \( F(1,36) = 100.4, \ p < 0.001 \), and the uncertainty \( \times \) noise \( \times \) frequency interaction was marginally significant, \( F(2,72) = 2.97, \ p < 0.06 \). This three-way interaction reflected the finding that uncertainty raised thresholds by similar amounts in the low- and high-noise conditions with the 9 c/deg target but had a larger effect in the high-noise condition with the 1 and 3 c/deg targets. None of the interactions involving uncertainty and age group approached significance (\( F < 1 \) in all cases).

B. Phase-Uncertain Ideal Observer

Equation (1) assumes that a quantum-limited observer has a calculation efficiency of 1. Such is the case when there is no stimulus uncertainty. However, spatial phase was randomized in the current experiment, and the cues did not inform the observer about the target’s phase, and therefore calculation efficiency for a quantum-limited ideal observer would be less than 1 in our conditions. For conditions of complete phase uncertainty, Jeffress showed that, when \( \hat{d} \) is greater than approximately 0.6, ideal detection thresholds are well approximated by the equation

\[
E = \left( \hat{d}' + \frac{1}{\sqrt{2}} \right)^2 N, \tag{5}
\]

where \( E \) is stimulus contrast energy, \( \hat{d}' \) is the criterion level of detectability (1.2 in our experiments), and \( N \) is the spectral density of the external noise. We modified Jeffress’s equation to make it analogous to Eq. (1) by introducing terms for equivalent noise (\( N_i \)) and calculation efficiency (\( \eta \)):

\[
E = \left( \frac{\hat{d}' + \frac{1}{\sqrt{2}}}{\eta} \right)^2 (N + N_i). \tag{6}
\]

A comparison of Eqs. (1) and (5) indicates that the primary effect of phase-uncertainty is to increase the slope of the threshold versus noise curve from \( \hat{d}'^2 \) to \( (\hat{d}' + 1/\sqrt{2})^2 \). In other words, the ideal phase-uncertain observer has a reduced calculation efficiency relative to the ideal phase-certain observer.

According to Eq. (6), threshold contrast energy for a phase-uncertain detector is a linear function of the spectral density of the external noise. In all of the following analyses, we fitted lines to the thresholds measured in each observer in the low- and high-noise conditions, computed the line’s slope and intercept, and then derived calculation efficiency and equivalent noise, using Eq. (6). This procedure ignores the effects of spatial frequency uncertainty, but those effects are examined in Section 4.

C. Calculation Efficiency

Figure 5 shows calculation efficiency as a function of spatial frequency for both the no-uncertainty [Fig. 5(a)] and the frequency-uncertainty [Fig. 5(b)] conditions. Efficiency was lower in old observers, and the age difference was approximately constant across spatial frequencies. In addition, efficiency declined in both age groups with increasing spatial frequency. This result is qualitatively similar to previous reports that efficiency for detecting gratings embedded in noise declines as the number of cycles in the stimulus increases. Finally, average calculation efficiency was reduced in the frequency-uncertainty condition by 0.33 log unit in old observers and 0.24 log unit in young observers.

To quantify these observations, calculation efficiencies were submitted to a 2 (age group) \( \times \) 2 (uncertainty) \( \times \) 3 (spatial frequency) repeated-measures ANOVA. As was done for the analysis of detection thresholds, a log transform was used to stabilize the variance across conditions, but analyses of the raw scores yielded the same results. Observers with missing data were excluded from the analysis. The between-observers effect of age group, \( F(1,36) = 11.2, \ p < 0.002 \), and the within-observers effects of uncertainty, \( F(1,36) = 42.1, \ p < 0.001 \), and frequency, \( F(2,72) = 41.0, \ p < 0.001 \), were significant. The uncertainty \( \times \) frequency interaction was marginally significant, \( F(2,72) = 2.8, \ p < 0.07 \). Analysis of simple main effects showed that the interaction was due to the fact that increasing frequency uncertainty reduced calculation efficiency slightly more for 3 c/deg gratings than for 1 and 9 c/deg gratings. None of the other interactions approached significance.

D. Equivalent Noise

Averaged across all spatial frequencies, equivalent noise in the no-uncertainty condition was \( 2.06 \times 10^{-5} \) deg and \( 6.91 \times 10^{-6} \) deg for old and young observers, respectively. To gain some appreciation of the magnitudes of these numbers, we can use Eq. (4) to convert these noise values, which are expressed in the same units as contrast energy, to contrast: The noise contrasts were 0.002 and 0.0034 in old and young observers, respectively. Averaged across all spatial frequencies, equivalent noise in the frequency-uncertainty condition was \( 4.46 \times 10^{-6} \) deg and \( 1.09 \times 10^{-6} \) deg in old and young observers, respectively, which corresponds to contrasts of 0.0016 and 0.0025, respectively. There were two conditions in which the average equivalent noise was less than zero: In the no-uncertainty, 3 c/deg condition equivalent noise was \( -6.4 \times 10^{-7} \) in old observers, and in the frequency-
uncertainty, 3 c/deg condition equivalent noise was 2 in young observers. The most likely explanation for these negative numbers is that they are due to measurement error. If the true equivalent noise is small, then measurement error would naturally lead to some negative values. For example, a negative noise could occur if threshold in the low-noise condition was unusually low and threshold in the high-noise condition was high, or if thresholds in both conditions were unusually low. To quantify how likely negative values of equivalent noise would be, we used Monte Carlo simulations to determine the mean and standard deviation of the equivalent noise that would be expected from groups of 24 observers that had detection thresholds like those shown in Fig. 3. In other words, we assumed that the data in Fig. 3 were good estimates of the population means and variances for detection thresholds, used these parameters to generate 10,000 synthetic sets of 24 low-noise and high-noise thresholds, and calculated the average equivalent noise for each set. When the sets were generated with thresholds from old observers in the no-uncertainty, 3 c/deg condition, the average equivalent noise was 1.78 x 10^{-5} deg, the standard deviation was 5.6 x 10^{-4} deg, and 44% of the sets had an average equivalent noise that was less than zero. With thresholds for young observers in the frequency-uncertainty, 3 c/deg condition, the average equivalent noise was 1.9 x 10^{-5} deg, the standard deviation was 1.8 x 10^{-4} deg, and 18% of the sets had an average equivalent noise that was less than zero. In both cases the difference between the simulated average equivalent noise and the one measured in the experiment was less than 0.1 standard deviation. Furthermore, both simulations suggest that obtaining a negative equivalent noise from a group of 24 observers is not unusual, given the variability associated with the threshold estimates. Thus it seems likely that the negative equivalent noises simply reflect measurement error.

Figure 6 shows equivalent noise as a function of spatial frequency for both the no-uncertainty [Fig. 6(a)] and frequency-uncertainty [Fig. 6(b)] conditions. In the no-uncertainty condition, mean equivalent noise was lower in old observers than in young observers when the target frequency was 3 c/deg and was higher in old observers than in young observers at 1 and 9 c/deg. In the frequency-uncertainty condition, equivalent noise was lower in old observers at 1 and 9 c/deg but essentially identical in both groups at 3 c/deg. In old observers equivalent noise was essentially invariant across spatial frequency in the frequency-uncertainty condition but varied in the no-uncertainty condition. The opposite pattern of results was obtained with young observers: Mean equivalent noise was nearly invariant in the no-uncertainty condition but varied slightly in the frequency-uncertainty condition. Thus, unlike what was found with calculation efficiency, equivalent noise did not appear to differ systematically across age groups or across uncertainty conditions.

Even a casual inspection of Fig. 6 reveals that the variability of equivalent noise in the no-uncertainty condition varied substantially across spatial frequency and age groups. Also, inspection of the data revealed that the distributions of equivalent noise for old observers in the 1 and 9 c/deg no-uncertainty conditions were highly skewed. The degree of skewness is illustrated in Fig. 6(a), which shows the median equivalent noises for old and young observers at 1 and 9 c/deg: For old observers, but not young observers, the medians were significantly lower than the means. We were not able to find a transformation that normalized and stabilized the variances, and so we did not submit the data to an ANOVA. Instead, we analyzed the data from the no-uncertainty condition with a nonparametric test (Mann–Whitney U test) and the data from the frequency-uncertainty condition in a separate 2 (age group) x 3 (frequency) repeated-measures ANOVA. Observers with missing data in the
To test the effect of spatial-frequency uncertainty, data from young observers were submitted to a 2 (uncertainty) × 3 (spatial frequency) ANOVA. Two observers with missing data were excluded from the analysis. Only the uncertainty × frequency interaction was significant, $F(2, 42) = 4.59, p < 0.02$. Post hoc tests indicated that equivalent noise at 3 c/deg was significantly lower in the frequency-uncertainty condition than in the no-uncertainty condition but that equivalent noise at 1 and 9 c/deg did not differ as a function of uncertainty. The effect of frequency uncertainty on equivalent noise in old observers was tested at each spatial frequency with a Wilcoxon signed ranks test. None of the tests approached statistical significance.

In summary, the analyses of equivalent noise did not find evidence of a consistent age difference in either the no-uncertainty or the frequency-uncertainty conditions. Also, equivalent noise within each age group did not vary consistently with the degree of spatial-frequency uncertainty.

E. Low-Luminance Control Experiment (Detection Thresholds)

Detection thresholds from the low-luminance control experiment, expressed in terms of contrast energy, are plotted against spatial frequency in Fig. 7. Also shown in Fig. 7 are thresholds from young and old observers in the no-uncertainty condition of the main experiment. In the low-noise condition [Fig. 7(a)], detection thresholds in the low-luminance control observers were virtually identical to thresholds measured in old observers. In the high-noise condition [Fig. 7(b)], thresholds in low-luminance control observers were lower than thresholds in old observers at 1 and 9 c/deg; at 3 c/deg thresholds in the two groups were similar.

Log-transformed thresholds from the control experiment and the main experiment were combined and analyzed initially in a 3 (group) × 3 (spatial frequency) × 2 (noise level) repeated-measures ANOVA. Observers with missing data were excluded. All of the main effects were statistically significant, as were the noise × frequency [$F(2, 130) = 8.2, p < 0.001$] and noise × frequency × group [$F(4, 130) = 2.8, p < 0.03$] interactions. The data in the low- and high-noise conditions were then submitted to separate 3 (group) × 3 (spatial frequency) repeated-measures ANOVA's. In the low-noise condition the main effect of spatial frequency, $F(2, 132) = 170, p < 0.001$, and the frequency × group interaction, $F(4, 132) = 5.8, p < 0.001$, were significant. Analyses of simple main effects indicated that thresholds from old observers and from the low-luminance group each differed from the young group's threshold at 9 c/deg. No other differences were significant. In the high-noise condition the main effects of group, $F(2, 65) = 4.5, p < 0.014$, and spatial frequency, $F(2, 130) = 87.5, p < 0.001$, were significant. The group × frequency interaction did not approach significance, $F(4, 130) = 1.1$. Differences between groups were assessed by summing the log-transformed thresholds across spatial frequencies for each observer and then submitting the summed scores to a one-way, between-observers ANOVA. The summing procedure was appro-
appropriate because the frequency × group interaction was not significant. Of course, the effect of group was identical to the one obtained in the main analysis, and post hoc comparisons [Fisher least significant difference (LSD), \( p < 0.05 \)] indicated that both the low-luminance group and the young group differed from the old group but that the low-luminance and young groups did not differ from each other.

In summary, the statistical analyses demonstrated that the low-luminance group's detection thresholds in low noise were most similar to those obtained from old observers in the main experiment but that their thresholds in high noise were most similar to those obtained from young observers in the main experiment.

**F. Low-Luminance Control Experiment (Calculation Efficiency)**

Average calculation efficiency for each spatial frequency is shown in Fig. 5(a). Efficiencies measured at low luminance were similar to those measured in young observers at high luminance, and they were higher than those measured in old observers at each spatial frequency. The low-luminance efficiencies and the efficiencies measured in old and young observers in the main experiment were analyzed in a 3 (group) × 3 (spatial frequency) repeated-measures ANOVA performed on log-transformed data. The main effects of group, \( F(2, 62) = 3.24, p < 0.05 \), and spatial frequency, \( F(2, 124) = 76.4, p < 0.001 \), were statistically significant. The frequency × group interaction did not approach statistical significance, \( F(4, 124) = 1.02 \), and therefore differences between groups were examined by summing efficiencies across spatial frequencies for each observer and then submitting the summed scores to a one-way, between-observers ANOVA. The effect of group was identical to the one obtained in the main analysis, and post hoc comparisons (Fisher LSD, \( p < 0.05 \)) indicated that both the low-luminance group and the young group differed from the old group but that the low-luminance and young groups did not differ from each other. Thus calculation efficiency in the low-luminance group was most similar to efficiencies measured in young observers.

**G. Low-Luminance Control Experiment (Equivalent Noise)**

Equivalent noise for the low-luminance conditions are shown in Fig. 6(a). As was found with old observers, the variance of the data differed significantly across conditions. Also, the distribution of equivalent noise at 9 c/deg was skewed, as can be seen by comparing the median and mean at that spatial frequency [see Fig. 6(a)]. Thus, at each spatial frequency, the equivalent noise from old and young observers in the main experiment and observers in the low-luminance control experiment were analyzed with a nonparametric test (Kruskal–Wallis). Significant group differences were found at 3 c/deg (Kruskal–Wallis statistic = 7.7, \( p < 0.02 \)) and 9 c/deg (Kruskal–Wallis statistic = 11.1, \( p < 0.004 \)). Post hoc Mann–Whitney U tests indicated that the difference at 3 c/deg was caused by the fact that young observers had higher equivalent noise than both the old and control groups but that the old and control groups did not differ from each other. At 9 c/deg, post hoc tests showed that the control group had higher equivalent noise than both the old and young groups. Thus, equivalent noise in the low-luminance control group was similar to old and young observers except at 9 c/deg, where it was significantly higher.

**4. DISCUSSION**

Most studies of the effects of aging on photopic contrast sensitivity have reported little or no age-related loss in contrast sensitivity at low frequencies and losses of 0.3–0.5 log unit at medium and high spatial frequencies. We obtained a qualitatively similar pattern of results in our low-noise, no-uncertainty condition. Contrast energy detection thresholds were nearly identical in both age groups at 1 and 3 c/deg but were elevated by 0.3 log unit in old observers at 9 c/deg [see Fig. 3(a)]. Expressing
thresholds in terms of contrast rather than contrast energy halves the age difference at 9 c/deg to 0.15 log unit. The smaller age difference found in the current study could simply reflect variability in the samples of old observers across experiments, which may be considerable. It may also reflect real differences in experimental procedures. Unlike previous studies, the current experiment used procedures that ought to have minimized age differences in uncertainty for the spatial frequency, orientation, and phase of the target. If, in the absence of such procedures, stimulus uncertainty has a greater impact on the performance of old observers, then age differences in sensitivity should be smaller with our testing procedures.

Calculation efficiency was lower in old observers than in young observers, including those young observers in the low-luminance control experiment. The differences were small—of the order of 0.2 log unit—but they occurred at all three spatial frequencies at both levels of uncertainty and were statistically robust. Pardhan et al. reported efficiencies of 0.27 and 0.19 for young and old observers, respectively, for a 6 c/deg target embedded in static noise. These efficiencies are comparable with those we obtained in the no-uncertainty condition at 1 c/deg, but are much higher than the ones we obtained at 3 and 9 c/deg. The difference in absolute efficiencies might reflect differences in the stimulus conditions used in the two studies. For example, the current study used one-dimensional noise, whereas Pardhan et al. used two-dimensional noise. Also, the phase of the target grating was randomized in the current study but was held constant in the study of Pardhan et al. Whatever the cause of the difference in absolute levels of efficiencies, it is important to note that the ratio of efficiencies of old and young observers was similar in the two studies.

Spear et al. reported that spontaneous firing rates in lateral geniculate nucleus cells were slightly higher in old macaque monkeys than in young monkeys. If this difference in noise persists at subsequent stages in visual processing, then it could conceivably manifest itself as a difference in equivalent noise. Increased optical blur in old observers could also manifest itself as an age difference in equivalent noise. However, we did not find any evidence of a consistent age difference in equivalent noise. The estimates of equivalent noise were considerably more variable in old observers than in young observers, especially in the no-uncertainty condition, and so our failure to find consistent age differences should be interpreted with caution. Nevertheless, the current results are similar to those reported by Pardhan et al., who found no age difference in (two-dimensional) equivalent noise at 6 c/deg.

Using a different masking paradigm from the one used here, Speranza et al. also found no age difference in equivalent noise at 1.5 and 3 c/deg.

There is one aspect of the current findings that is consistent with the idea that equivalent noise is lower in old observers than in young observers, but that the experiment lacked sufficient statistical power to detect the difference. Recall that the logarithmic differences between detection thresholds from old and young observers were higher when the targets were embedded in high levels of external noise, especially for 1 and 3 c/deg targets (see Fig. 3). It is important to note that this effect of noise on detection threshold cannot be due to differences in calculation efficiency. A change in calculation efficiency produces a change in the slope of the detection versus noise curve when it is plotted in linear coordinates (see Fig. 1). So, if two observers differ solely in efficiency, then the ratio of their thresholds at each level of external noise will be constant. In other words, if thresholds are plotted in log–log coordinates, then a difference in calculation efficiency simply shifts the detection versus noise curve vertically without altering its shape and the logarithmic difference between the curves remains constant. Therefore, according to the model in Fig. 2, the increase in the log difference between thresholds from the two age groups implies that equivalent noise is lower in old observers. In this regard it is interesting to note that the median equivalent noise was lower in old observers in five out of six conditions, the one exception being the 9 c/deg, no-uncertainty condition. Pardhan et al. also found that average equivalent noise at 6 c/deg was lower in old observers, although not by a statistically significant amount.

A. Effects of Stimulus Uncertainty

Increasing spatial-frequency uncertainty reduced calculation efficiency by an average of 0.33 and 0.24 log unit in old and young observers, respectively. To calculate how much of this decline can be attributed to changes in the task, we used computer simulations to compute the performance of a detector that monitored the responses of one channel (in the no-uncertainty condition) or three independent channels (in the frequency-uncertainty condition). In separate sets of simulations of the frequency-uncertainty condition the responses of the three channels were combined using the summation-of-responses and maximum-response rules. When using the summation-of-responses rule, the detector’s decision was based on the sum of the channel responses. With the maximum-response rule, the detector’s decision was based on the channel that yielded the largest response. Both combination rules are less than optimal, but the maximum-response rule is nearly optimal for signals like the ones used in the current experiment. We used simulations to calculate the model’s thresholds for sinusoidal signals embedded in different amounts of noise and then used Eq. (6) to derive the model’s calculation efficiency compared with the phase-uncertain ideal observer. Details of the simulation are given in Ref. 36. Precise estimates of the effects of spatial-frequency uncertainty depend on the assumed bandwidths of the underlying channels and on the rule for combining responses across channels. We do not have sufficient data to develop a quantitative model of spatial-frequency uncertainty, and so instead we present two results that do not appear to be strongly dependent on the simulation parameters.

The initial simulations computed the effects of stimulus uncertainty on a detector that encoded each target frequency with a rectangular filter that had a bandwidth of 1 c/image. With no uncertainty, the simulation yielded a calculation efficiency of 0.97. With uncertainty, the simulation yielded calculation efficiencies of 0.65 and 0.63 for the maximum-response and summation-of-response rules, respectively. Thus spatial-frequency uncertainty reduced simulated calculation efficiency by 0.16 log unit.
We then determined whether this effect of uncertainty depended on the bandwidth of the individual filters: It did not. Increasing filter bandwidth (W) reduced simulated calculation efficiency (J) according to the equation

\[ J = 1/W^{0.4}, \]

but the ratio of efficiencies in the no-uncertainty and frequency-uncertainty conditions remained the same. Thus it appears that approximately half of the uncertainty effect found in real observers can be attributed to the effects of uncertainty per se.

Our simulations yielded one other interesting result. To account for the fact that calculation efficiency varied significantly with spatial frequency [see Fig. 5] it was necessary to assume that channel bandwidth was proportional to the channel’s center frequency, which is consistent with psychophysical and physiological evidence that spatial-frequency bandwidth is constant on a logarithmic scale.37 With this added assumption, simulated calculation efficiency in the no-uncertainty condition declined with increasing spatial frequency when both the maximum-response and summation-of-responses rules were used. Simulated calculation efficiency in the frequency-uncertainty condition also declined with increasing spatial frequency when the maximum-response rule was used. Both predictions are qualitatively consistent with the results in Fig. 5. However, simulated efficiency in the frequency-uncertainty condition was constant across spatial frequencies when the summation-of-responses rule was used. The reason for this result is that the summation-of-responses rule essentially creates one broadband linear filter from the narrower filters feeding into it, and therefore calculation efficiency in the frequency-uncertainty condition is determined solely by the sum of the bandwidths of the individual filters. Although several authors have suggested that the summation-of-responses rule adequately accounts for the way detection thresholds vary with uncertainty,26,38,39 our results suggest that it may have difficulty accounting for the way efficiency changes with uncertainty.

B. Effects of Reduced Retinal Illuminance

A control experiment measured the effect of reducing average luminance from 80 to 1.6 cd m\(^{-2}\) on detection thresholds in young observers. When the targets were embedded in low noise, reducing luminance raised threshold for the 9 c/deg target by 0.36 log unit. This change in threshold is similar to previous measures of the effects of luminance on contrast sensitivity.40 When the targets were embedded in high noise, reducing luminance had no statistically significant effect on detection threshold. Again, this result is consistent with previous reports that detection thresholds for patterns embedded in high levels of external noise are nearly constant across a wide range of average luminance.44

The main purpose of the control experiment was to evaluate the dark glasses hypothesis. According to this hypothesis, age differences in contrast sensitivity are due solely to differences in optical and/or receptor mechanisms that reduce the proportion of photons at the cornea that are transduced by photoreceptors, and therefore sensitivity in old observers should be similar to sensitivity in young observers who view the stimulus at a lower retinal illuminance. Interestingly, old observers and low-luminance control observers did indeed have similar thresholds at all spatial frequencies when the patterns were embedded in a low level of external noise. This finding is consistent with the idea that reduced contrast sensitivity in old observers at higher spatial frequencies is linked somehow to a reduction in retinal illuminance. However, other aspects of the results make it unlikely that the dark glasses hypothesis can provide a complete account of the current findings. One problem is that the difference between retinal illuminance in old and young observers is almost certainly smaller than the one produced in our control experiment. Although we did not measure pupil size, both classical data41 and more recent measurements42 indicate that reducing average luminance from 80 to 1.6 cd m\(^{-2}\) should have reduced retinal illuminance in our young observers by approximately 1.3 log units. However, age differences in pupil size and in the optical density of the ocular media are estimated to change retinal illuminance by only 0.3–0.5 log unit between the ages of 20 and 65.45 If our control experiment had varied illuminance over this smaller range, then the elevation in contrast sensitivity at 9 c/deg would have been much smaller than the 0.36 log unit change that we observed.45

One might argue that aging produces neural changes that further reduce the proportion of quanta captured by retinal cells and therefore that the effective retinal illuminance in old observers is much lower than the illuminance passed by the optics. Age-related changes in cone pigment density estimated with retinal densitometry46,47 and psychophysical techniques48–50 are consistent with this idea. Nevertheless, even if we assume that such neural changes are sufficiently large so that the proportion of photons captured by the receptor mosaic was similar in old observers and low-luminance control observers, the dark glasses hypothesis still fails to account for the effects of external noise. Specifically, the dark glasses hypothesis makes the incorrect prediction that raising the level of external noise should have similar effects on thresholds from both groups. Reducing retinal illuminance increases equivalent noise but does not change calculation efficiency,16 whereas aging lowers calculation efficiency but does not produce consistent changes in equivalent noise [Figs. 5(a) and 6(a)]. Thus age differences in calculation efficiency imply that some factor besides reduced retinal illuminance must contribute to lower contrast sensitivity in old observers.

C. Age Differences in Calculation Efficiency

According to the model shown in Fig. 2, age differences in optics cannot produce changes in calculation efficiency. Optical dysfunctions that increase blur and/or light scatter attenuate the signal and the level of the external noise but do not alter the external signal-to-noise ratio. Thus these types of optical problems ought to shift the contrast detection versus noise functions laterally along the noise axis without altering its slope and consequently change equivalent noise but not calculation efficiency (see Fig. 1). In agreement with the theory, Pardhan et al.18 reported
that patients with cataracts had elevated equivalent noise but normal calculation efficiency. Theoretically, it is possible that decreased retinal illuminance or reduced photon absorption by photoreceptors in old eyes could induce neural changes that result in a loss of efficiency. However, the results of our low-luminance control experiment, as well those from previous studies, show that the effect of reducing luminance is to raise equivalent noise but leave efficiency unchanged. Thus age differences in calculation efficiency almost surely are due to differences in neural mechanisms beyond the site of photon absorption. Age-related changes in the pattern electroretinogram and visually evoked potentials are consistent with this proposal.

The factors that might contribute to lowered calculation efficiency can be divided into two main categories. One category consists of processes or mechanisms that produce an internal noise that grows proportionally with the input. This multiplicative noise could be associated with sensory processes that encode the stimulus or with more central mechanisms related to decision processes. There is good physiological evidence that multiplicative noise affects the contrast response of cortical cells in the cat and the monkey, and several psychophysical demonstrations have suggested that multiplicative noise affects visual and auditory detection in human observers, so it is likely that multiplicative noise lowers calculation efficiency in young observers. However, we know of no physiological or psychophysical studies that have examined how multiplicative noise changes with age. Thus it remains an open question whether age differences in multiplicative noise are partly responsible for age differences in calculation efficiency.

The second category of processes or mechanisms that lower calculation efficiency are those that produce a poor match between the spatiotemporal characteristics of the stimulus and those of the neural filter used to detect it. A poor match could be obtained in at least two ways. First, if we assume that stimuli are encoded with multiple filters, and that one of the tasks an observer faces when trying to detect a stimulus is to determine which filter to monitor, then a poor match could occur if an observer failed to select the optimal filter. For example, the observer might not be sure of the target’s phase and therefore monitor the response of a filter that was not positioned optimally. Or the observer might not be sure about the target’s spatial frequency and therefore monitor the response of an off-frequency filter or pool the responses across a range of spatial frequencies. Thus age differences in stimulus uncertainty might contribute to differences in calculation efficiency. However, it is unlikely that age differences in phase or temporal uncertainty contributed to differences in calculation efficiency in the current study, because the stimulus conditions should have minimized age differences on those dimensions. Moreover, the effects of spatial-frequency uncertainty were similar in both age groups. If uncertainty affects threshold by changing the number of filters that an observer must monitor in a detection task, then our results show the number of monitored channels changed by similar amounts in old and young observers. The results therefore are inconsistent with the hypothesis that old observers always monitor a wide range of spatial-frequency filters. However, the results do not rule out the possibility that old observers are slightly less selective (i.e., monitor slightly more channels) than young observers at all levels of external uncertainty.

The second way that a mismatch between filter and stimulus might occur is when the optimal filter for a task simply is not available to the observer. For example, the target’s contrast energy might be packed into a narrow range of spatial frequencies, but observers may lack narrow-band mechanisms and therefore be forced to monitor the outputs of more broadband (and therefore nonoptimal) filters. Thus age differences in calculation efficiency may reflect changes in the tuning or spatial summation characteristics of spatial-frequency channels rather than an ability to select the best channel for a particular task. Unfortunately, little is known about age-related changes in spatial-frequency channels. For instance, although previous studies have shown that Ricco’s area changes with age, there are no published data on grating summation in old observers. Furthermore, only one study has compared spatial-frequency tuning in old and young observers. Ozin and Bennett measured the spatial-frequency selectivity of the mechanism used to detect a 4 c/deg grating embedded in low-pass or high-pass noise. Spatial-frequency bandwidth, estimated by noting how masking varied as a function of the noise cutoff frequency, was 0.2 octaves broader in old observers. This increase in bandwidth is too small to account for the age differences in calculation efficiency observed in the current study. However, the characteristics of the noise, as well as the size and duration of the grating stimulus, used by Ozin and Bennett differed considerably from the ones used here, and so it would be premature to rule out age-related changes in spatial-frequency tuning as a factor that contributes to changes in calculation efficiency.

### D. Effects of External Noise

Unlike typical everyday visual tasks, most clinical (and psychophysical) tasks involve a single stimulus presented against a uniform field and use procedures that minimize the observer’s uncertainty about the target. One of the goals of the current study was to examine how two features of everyday tasks, namely, the presence of a noisy background and some degree of stimulus uncertainty, affect age differences in a 2AFC detection task. Both noise and uncertainty affected thresholds, but only the noise manipulation affected age differences in performance. These results suggest that background noise or visual clutter might have a greater impact than stimulus uncertainty on the performance of old adults in everyday tasks, at least those tasks in which observers are not forced to respond quickly.

At a qualitative level, the current findings are consistent with previous studies of age-related changes in selective attention, which show that old observers are more prone to distractor interference than are young observers. This similarity raises the possibility that deficits in visual detection and deficits in selective attention may be related. One obvious possibility is that visual detection and selective attention tasks tap into similar or overlapping sets of visual mechanisms. Another
possibility is that age-related changes in these tasks are due to general, nonspecific changes in the aging brain. Consistent with this view, recent studies have found that age-related changes in tasks that are thought to tap sensory mechanisms (e.g., visual acuity) are correlated with age-related changes in a wide range of cognitive tasks. To determine whether age differences in visual detection and selective attention tasks reflect changes in task-specific or more general mechanisms, future studies should examine the relationship between performance on a variety of visual and cognitive tasks within one subject population.

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REFERENCES AND NOTES

15. The performance of a quantum-limited observer is constrained by quantal fluctuations, and therefore one might expect the threshold versus noise curve to intercept the abscissa at the spectral density of the photon noise. However, in our framework photon noise is an external noise added to the stimulus. If it were possible to reduce photon noise, then the quantum-limited threshold would approach zero. Pelli showed that the spectral density of photon noise equals the reciprocal of the photon flux and that it is approximately two orders of magnitude less than the spectral density of the equivalent noise estimated in most grating detection experiments. Our experiments used one-dimensional static noise and did not consider the effects of photon noise.
20. Luminance quantization altered the contrast of the sine wave gratings and noise used in these experiments. The lowest detection thresholds were obtained with the 1 c/deg target with no frequency uncertainty, so the effects of quantization should have been greatest in that condition. We therefore examined the possible effects in that condition. First, in software we re-created the stimulus luminance profiles presented on the screen when pattern contrast was set to detection threshold, and we counted the number of luminance steps in the pattern. At detection threshold (e.g., contrasts of 0.014 and 0.015 for young and old observers, respectively), the gratings had four luminance steps and 95% of the stimulus power was concentrated at the nominal target frequency. The number of luminance steps did not drop below four until stimulus contrast was reduced below 0.01. Thus the quantization effects were small, even for stimuli presented at detection threshold. Next, we examined the raw data to find observers who might have had thresholds below 0.01 by looking for observers who consistently responded correctly for contrasts as low as 0.01. Four old observers and four young observers met this criterion. We then replaced thresholds for those observers with a value of 0.007, which was approximately one half of the average threshold and was the smallest contrast that could be produced with our equipment, and repeated all of our statistical analyses. The results of the new analyses were identical to those reported in Section 3. Thus luminance quantization does not appear to have had a significant effect on our results.
22. Some old observers had trouble manipulating the keyboard while viewing the patterns. For these observers the experimenter pressed the key that corresponded to the pattern indicated verbally by the observer. To eliminate any effects of experimenter bias, the experimenter’s view of the display was blocked during each trial.
25. Thresholds from individual subjects are available from P. J. Bennett on request.


28. For the case in which phase is unknown, the noise and signal-plus-noise distributions for the ideal detector are neither normal nor constant variance. Strictly speaking, therefore, Eq. (5) applies to the detection index $d_s$, not $d'$. When the distributions are normal and constant variance, $d_s = d'$.

29. Previous studies have shown that detection versus noise curves obtained from young observers are linear. Pardhan et al.18 obtained similar results with old observers. However, those previous studies used conditions in which position uncertainty was minimized, whereas position uncertainty was maximized in the current experiment. We therefore conducted a preliminary experiment to examine whether contrast versus noise functions were linear in our stimulus conditions. The experiment was identical to the no-uncertainty condition in the main experiment except that four levels of external noise (contrast standard deviations of 0.04, 0.09, 0.16, and 0.25) were used. Four young observers (23–33 years; median age at 24 years) and one old observer (63 years) were tested. Multiple thresholds were obtained at each level of external noise, and the best-fit straight line was computed for the data from each observer. In all cases, thresholds were well fit by a straight line ($R^2 > 0.87$) and the quadratic component of the regression was not statistically significant. Efficiency and equivalent noise were calculated by first fitting the equation $E_m = b + J/(d' + 1/\sqrt{2})^2$. According to Eq. (6), $d' = (1/m) \times (d' + 1/\sqrt{2})^2$. $E_m$ is the line's slope, and $b$ is the line's intercept. According to Eq. (6), $J = (1/m + 1/\sqrt{2})^2$. $J$ is the external noise's spectral density, $m$ is the line's intercept. According to Eq. 36.


36. The simulation consisted of 2AFC trials in which a detector was presented with a noise stimulus and a signal-plus-noise stimulus. The noise stimulus was an array of random numbers drawn from a zero-mean Gaussian distribution. The signal-plus-noise stimulus was another array of Gaussian random variables to which was added a sine wave target in random phase. The detector decided which stimulus contained the target by computing the power in a frequency band centered on the target frequency and selecting the stimulus with the greatest power. The Gaussian noise consisted of two components, one fixed and the other variable. The fixed component represented the detector's internal noise and was held constant. The variable component represented the external noise and was varied across simulations to compute the detector's calculation efficiency. The detector's threshold was computed by measuring percentage correct for 400 simulated trials at each of 12 simulated target amplitudes, fitting a Weibull function to the data, and calculating the 81% correct point. Thresholds were measured for five levels of external noise, and Eq. (6) was used to estimate the detector's calculation efficiency and internal noise. As expected, the calculation efficiency of the simulated ideal detector (filter bandwidth = 1 c/deg) was 1. Next, calculation efficiency was computed for a detector with a filter bandwidth ($W$) that ranged from 1 to 30 c/deg. Across this range, efficiency was nearly constant, approximately 0.87. Finally, spatial-frequency uncertainty was simulated by forcing the detector to compute power at three bands of spatial frequencies centered at 10, 30, and 90 c/deg. The bandwidth of each channel was varied with the restriction that the three frequency bands never overlapped. The power from each band was combined in two ways. In the maximum-response simulations, the detector chose the stimulus that yielded the largest number. In the summation-of-response simulations, the three numbers were added and the detector chose the stimulus that yielded the largest sum.


40. It is necessary to convert from units of space average luminance to retinal illumination to compare our results with previous measurements. We did not measure pupil diameters of the observers in our experiments, and so we estimated illumination in the following way. Subsequent to the main experiments, pupil diameters were measured on five young observers. Average pupil diameter was 5.5 mm for the high-luminance display. We were unable to measure pupil size reliably in the low-luminance condition, but previous studies have found that pupil diameter increases by 40–50% over this luminance range. On the basis of these measurements it is reasonable to assume that decreasing luminance from 80 to 1.6 cd m$^{-2}$ reduced retinal illumination from approximately 1900 to 80 td. Kelly reported that contrast sensitivity at 8 c/deg drops by approximately 0.4 log unit, whereas sensitivity for 1 and 3 c/deg remains nearly constant, over this range of retinal illuminances. These values do not differ appreciably from those found in the current study at 9, 3, and 1 c/deg.


52. W. A. Wickelgren, "Unidimensional strength theory and