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Measuring contrast sensitivity

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ABSTRACT

Contrast sensitivity defines the threshold between the visible and invisible, which has obvious significance for basic and clinical vision science. Fechner's 1860 review reported that threshold contrast is 1% for a remarkably wide range of targets and conditions. While printed charts are still in use, computer testing is becoming more popular because it offers efficient adaptive measurement of threshold for a wide range of stimuli. Both basic and clinical studies usually want to know fundamental visual capability, regardless of the observer's subjective criterion. Criterion effects are minimized by the use of an objective task: multiple-alternative forced-choice detection or identification. Having many alternatives reduces the guessing rate, which makes each trial more informative, so fewer trials are needed. Finally, populations who may experience crowding or target confusion should be tested with one target at a time.

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1. Introduction

Suppose we present a visual target on a uniform background. The *contrast* of the target quantifies its relative difference in luminance from the background, and may be specified as Weber contrast $\frac{L_{max}-L_{min}}{L_{backround}}$, Michelson contrast $\frac{L_{max}-L_{min}}{L_{max}+L_{min}}$, or RMS contrast $\frac{L_\sigma}{L_\mu}$, where L_{max}, L_{min}, $L_{background}$, L_μ, and L_σ are luminance maximum, minimum, background, mean, and standard deviation, respectively. Weber contrast is preferred for letter stimuli, Michelson contrast is preferred for gratings, and RMS contrast is preferred for natural stimuli and efficiency calculations (Bex & Makous, 2002; Pelli & Farell, 1999). *Threshold* contrast is the contrast required to see the target reliably. The reciprocal of threshold is called *sensitivity*.

Vision science, with the ultimate goal of providing a mechanistic account for how we see, has placed a great emphasis on measuring and explaining sensitivity for a wide range of target objects in a wide range of conditions. Fechner's 1860 book, *Elemente der Psychophysik*, was the beginning of the modern era. His title introduced the word, *psychophysics*, referring to behavioral studies of perception. In his words, psychophysics works towards "an exact theory of the functionally dependent relations of . . . the physical and psychological worlds." (Fechner, 1860; /1966, p. 7). He reviewed the prior work on contrast sensitivity, and described and named many of the basic procedures that we still use today to measure threshold (and thus sensitivity). Reviewing his own, and past measurements, especially

(Masson, 1845), Fechner reported that threshold contrast is about 1% for a wide range of targets, independent of size and luminance. That amazing and robust finding is still unexplained today. The roughly 1% holds up, for example, as the threshold contrast (log contrast -1.8 ± 0.1, about 1.6%) for identification of Sloan letters over a sixteen-fold range of size (0.75–12°) and hundred-fold range of luminance (7–514 cd/m²) (Zhang, Pelli, & Robson, 1989).

Generalizing earlier results from fluctuation theory, Signal Detection Theory showed that in white noise, the detectability of a known signal depends solely on its contrast energy, independent of its shape or extent. The noise level determines the minimum detectable contrast energy (Pelli & Farell, 1999; Peterson, Birdsall, & Fox, 1954). That is for the optimal algorithm, or ideal observer. Since, in a given level of white noise, all signals have the same ideal threshold energy, we can say that the ideal detection thresholds conserve contrast energy:

$$E = C_{rms}^2 AT = k \tag{1}$$

where E is contrast energy, c_{rms} is RMS contrast, A is area, T is duration, and k is a constant. For a fixed luminance, this corresponds to Eq. (1) in Barlow (1958). For a fixed duration T, this is Piper's law (Piper, 1903). Barlow notes that, far from being the rule, Eq. (1) holds only for small-area short-duration stimuli. Unlike Eq. (1), Fechner's review showed that human threshold contrast is independent of size over a wide range of size. When size increases, the ideal threshold (in white noise) conserves energy while the human threshold conserves contrast (Dubois, Poeppel, & Pelli, 2013; Pelli, Farell, & Moore, 2003; Pelli et al., 2006). This is yet to be explained, as noted above, but can be understood as an early informational bottleneck in object recognition (Dubois, Poeppel, & Pelli, 2013).

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Robson (1993) reviews the history of contrast sensitivity measurement and Owsley (2003) reviews its importance for clinical assessment. We present some highlights. Contrast sensitivity is impaired in many clinical conditions and peak contrast sensitivity may be reduced even when acuity is normal. Contrast sensitivity is impaired in ophthalmic conditions including myopia (Collins & Carney, 1990), glare (Abrahamson & Sjöstrand, 1986), cataract (Hess & Woo, 1978), amblyopia (Freedman & Thibos, 1975), age-related macular degeneration (Kleiner et al., 1988), ocular hypertension (Gandolfi, 2005), glaucoma (Stamper, 1984) and dry eye (Rolando et al., 1998). Contrast sensitivity can also be impaired in neurological conditions, including cerebral lesions (Bodis-Wollner, 1972), multiple sclerosis (Regan et al., 1981), Parkinson's disease (Bodis-Wollner & Onofrj, 1986) and schizophrenia (Cimmer et al., 2006). Furthermore, contrast sensitivity loss is a common side-effect of many prescription drugs (Li, Tripathi, & Tripathi, 2008; Santaella & Fraunfelder, 2007). Some contrast sensitivity deficits can be remedied by optical, pharmaceutical, surgical, or rehabilitative intervention. Even when poor contrast sensitivity cannot be remedied, patients may be glad to understand why they see poorly.

The French hydrographer Pierre Bouguer (1698–1758) made the first measurements of light, using the eye as a null indicator for a match. To assess the accuracy of the eye's match, he made the first measurement of contrast sensitivity (Bouguer, 1760/1961). His method is very simple. Two candles illuminate a screen. One candle is roughly ten times farther than the other. An opaque rod is placed between the far candle and the screen, casting a shadow onto the screen. That shadow is the target to be detected by the observer. The luminance difference across the edge of the shadow is determined solely by the far candle. The background luminance comes almost entirely from the near candle. Contrast is the target luminance difference expressed as a fraction of the background. To measure threshold, the contrast of the shadow is controlled by adjusting the distance of the far candle until the observer can barely see it.

Presuming that the candles have the same intensity and that their illuminations strike the screen at the same angle, as recommended by Bouguer, then the Weber contrast is approximately d^2/D^2, where d is the distance of the near candle and D is the distance of the far candle. The tiny contribution of the far candle to the background luminance is negligible. Using this technique, Bouguer (1760/1961) reported a threshold of 1/64, or about 1.6%, for one observer. A hundred years later, Fechner (1860/1966, p. 125) reported that Volkmann used this technique with four observers and consistently found a 1% threshold. More than 150 years later, in 2012, John Robson and Denis Pelli replicated Bouguer's conditions, using modern paraffin candles, and measured a threshold not significantly different from his.

Masson (1845) used a spinning disk. He painted black a tiny sector of a white disk. When spun quickly, this produces a gray ring with a contrast proportional to the width of the black sector. He too found a 1% threshold for "ordinary" to "good" vision, and reported that, over a wide range, there is no effect of size or illumination. Bouguer's candles allowed for easy adjustment of contrast, simply by moving the far candle. Masson's disks are not adjustable, and one finds threshold by testing with many disks. Both tests use a subjective task, asking whether the observer sees the target, which is always present.

2. On each trial: The task

Methods to measure contrast threshold can be broadly categorized into objective and subjective tasks (e.g. Pelli & Farell, 2010). *Objective* tasks have a right answer. *Subjective* tasks do not. In objective tasks, the observer is making a factual assertion about the stimulus, which is right or wrong. In subjective tasks, the observer is reporting his or her internal experience, which is private to the observer, so the experimenter cannot classify the report as right or wrong. Subjective tasks include rating, matching, and nulling. Objective tasks include yes/no (Is it present?) and forced-choice detection or identification.

When observers make a yes–no judgment, to detect a stimulus, it is now well established that they say "yes" if the internal magnitude of the stimulus sensation exceeds an internal criterion (Green and Swets, 1966). Many things, including instructions, can induce the observer to raise or lower his or her criterion, causing threshold to shift up or down. This unknown internal criterion of the observer typically differs among observers and may vary across populations and over time. Clinical and basic studies of visual sensitivity are usually not interested in these criterion shifts, so they avoid the undesired variations of yes/no methods by using less-criterion dependent methods (Vaegan & Halliday, 1982). Symmetric designs, with equally probable possibilities encourage observers to use a criterion that yields equally probable answers. In some popular forced-choice procedures the observer identifies a letter as one of the N possible letters, or identifies the orientation of a stimulus as one N orientations, or indicates which of N spatial or temporal intervals contained the target. The N possibilities are equally probable. Such forced-choice identification and detection tasks are the preferred methods for accurate estimation of contrast thresholds.

For detection, N is typically 2, and the task is usually two-interval forced choice (2IFC). There are two presentations, each marked by a tone. Only one contains the target. The observer must say which. Threshold is the contrast at which the observer's response is correct on a given percentage (e.g. 75%) of the trials. Near threshold, decisions take longer.

3. The trial sequence: Threshold estimation

In order to estimate a contrast threshold, the observer is tested over many trials, at various contrasts. Each trial is at some contrast and is scored right or wrong. The proportion of correct responses at each contrast is recorded. The observer's probability of correct response as a function of contrast is the *psychometric function*. There are several ways to select the contrast level to be tested on the current trial. The *method of constant stimuli* presents a predetermined set of contrasts in random order (Fechner, 1860/1966). This approach is easy to implement, but requires that the set of test contrasts be specified before the experiment begins. This often forces the experimenter to test an inefficiently broad range of contrasts, which is particularly problematic for special populations. Running 10 trials at each of 10 test contrasts requires 100 trials per threshold. Observers can typically complete ten trials per minute, but special populations may be slower, and may tire sooner. The wish to minimize the number of trials has led to the popularity of statistically efficient methods that use all the preceding responses to select the contrast level for the current trial that will be most informative in improving the threshold estimate. Such methods yield an accurate estimate of threshold after 40 trials.

More generally, *adaptive staircase* methods exploit existing knowledge of the likely parameters of the psychometric function for similar observers together with the results of previous trials on this observer to select a test level that provides maximum information about the psychometric function. There are many alternative adaptive staircase methods, including 3 down 1 up (Wetherill & Levitt, 1965), APE (Watt & Andrews, 1981), QUEST (Watson & Pelli, 1983), PEST (Taylor & Creelman, 1967), ZEST (King-Smith et al., 1994), and Ψ (Kontsevich & Tyler, 1999). For review see Treutwein (1995) and Leek (2001).

As noted above, in a forced-choice task, the experimenter asks the observer to identify one of many possible targets or to say which of several intervals (spatial or temporal) contained the target. The two-alternative forced-choice (2AFC) procedure with feedback concerning response accuracy is widely used to test experienced psychophysical observers (Blackwell, 1952). However, the slope of the psychometric function, and therefore the information gained from each response, increases with the number of alternatives because that decreases the probability of a successful guess. Multiple response alternatives reduce the guessing rate, as Snellen (1862) and Donders (1864) pointed out long ago. Most of this benefit is attained by having at least four or five alternatives (Pelli & Robson, 1991; Pelli, Robson, & Wilkins, 1988). When central viewing is not required, four spatial alternatives have been recommended for testing inexperienced observers (Jäkel & Wichmann, 2006).

The psychometric data (responses at several contrasts) generated by any of these methods are usually then fit with a psychometric function, which is one of several similar sigmoidal functions (Treutwein, 1995), with free parameters for threshold and slope, and a fixed parameter for the guessing rate and possibly a fourth (free or fixed) parameter for response mistakes (Wichmann & Hill, 2001a), arising from attention lapses, blinks, finger slips, etc. Algorithms are available to fit and estimate confidence intervals on each parameter (Kingdom & Prins, 2009; Wichmann & Hill, 2001a, 2001b).

4. The Contrast Sensitivity Function (CSF)

Schade (1956) made the first measurements of visual contrast sensitivity as a function of spatial frequency. This contrast sensitivity function (CSF) typically consists of the measured contrast detection threshold at five or so spatial frequencies uniformly spaced on a log scale spanning the most sensitive part of the range, typically 1–16 c/deg. The CSF is a product of optical and neural factors (Green & Campbell, 1965). Optically, the quality of the retinal image is determined by the Modulation Transfer Function (MTF), which depends strongly on pupil size, and can be measured physically (Artal & Navarro, 1994). Neurally, Campbell and Robson (1968) revealed the presence of multiple channels in vision, each selective to a different band of spatial frequencies. This greatly increased interest in measuring the CSF. Today, the set of thresholds as a function of spatial frequency is usually fit with a contrast sensitivity function (Watson, 2000). In order to establish the CSF of a standard human observer, a group of 10 laboratories collaborated to collect contrast thresholds for 16 observers on a standard set of 43 diagnostic stimuli (Carney et al., 2000). The resulting data were used to evaluate the goodness of fit of 5 (Watson, 2000) or 9 (Watson & Ahumada, 2005) competing CSF models. Several models provided approximately equally good fits to the data, with as few as four parameters.

The peak spatial frequency of the CSF shifts to larger sizes during normal aging (Owsley, Sekuler, & Siemsen, 1983) and lower luminance levels (De Valois, Morgan, & Snodderly, 1974), and when eye diseases like age related macular degeneration are present (Mei & Leat, 2007). In many pathologies, contrast sensitivity is impaired at all spatial frequencies, but a range of different clinical conditions selectively affect different regions of the CSF. For example, incorrect refraction reduces sensitivity to high spatial frequencies, without affecting sensitivity to low spatial frequencies (Charman, 1979; Green & Campbell, 1965), as does amblyopia (Freedman & Thibos, 1975); glare, which is a common side effect of refractive surgery (Ackermann et al., 2013), reduces sensitivity to low spatial frequencies with relatively little effect on acuity (Abrahamson & Sjöstrand, 1986), and fovea-sparing geographic atrophy from Dry AMD can reduce sensitivity only to large targets (Sunness et al., 1997). These sources of population variability,

along with measurement variability, increase the sample size required for clinical trials (Lesmes, Jackson and Bex, 2013).

How many degrees of freedom does the CSF have? Might one get by with fewer than four? Pelli, Rubin, and Legge (1986) suggested that a fixed-shape parabola might adequately fit clinical CSFs plotted as log contrast sensitivity as a function of log spatial frequency. That model has only two degrees of freedom: horizontal and vertical position of the parabola. If two degrees of freedom suffice, then measuring acuity and one contrast sensitivity (at a single size or spatial frequency) ought to be enough to estimate the whole CSF. To test this idea, Rohaly and Owsley (1993) fit one hundred CSFs of older patients and found that, to fit them all, they needed more that two degrees of freedom. As noted above, the simplest model so far needs 4 parameters to fit CSFs of normal observers.

5. Is it necessary to measure the whole CSF?

Straightforward measurement of the CSF at four spatial frequencies, with 40 trials per point, requires 160 trials. A standard CSF function, with four free parameters, can be fit to the results. Applegate, Hilmantel & Howland (1997) show that the area under the log CSF is a useful one-number of contrast sensitivity that is easy to correct for change in target size. Alas, 160 trials is prohibitive for routine clinical testing. If time is very limited, clinicians measure just acuity. With more time, many clinicians also measure low-contrast acuity (Bailey, 1982; Regan & Neima, 1983), or employ the Pelli-Robson contrast sensitivity chart, which measures threshold contrast for identification of a fixed size target letter (Pelli, Robson, & Wilkins, 1988). This two-number summary, high-contrast acuity and either low-contrast acuity or contrast threshold for a large letter, could be fit by one of the models to estimate the full contrast sensitivity function. In this spirit, Brown and Lovie-Kitchin (1989) found high correlations between the CSF and the high- and low-contrast acuities. Of course, with only two measurements and a four-parameter model, one might not get accuracy as good as would be achieved with four or more measurements. Since clinical time is so precious, it would be interesting to determine how the accuracy of the estimated CSF grows with the number of thresholds measured, from zero (just population norms) on up.

Recently, new methods use prior knowledge of the CSF and the distribution of its parameters to select the spatial frequency and contrast of each trial to maximize the information gain (Lesmes et al., 2006; Lesmes, Lu, Baek, & Albright, 2010; Vul, Bergsma, & MacLeod, 2010). These approaches provide significant gains in clinical data collection and have already demonstrated successful visual assessment in clinical populations with amblyopia (Hou et al., 2010), age-related macular degeneration (Lesmes et al., 2012) and congenital cataracts (Kalia et al., 2012). In these populations, reliable estimates of the CSF are possible within 25 trials and an estimate of the area under the log CSF in as few as 15 trials (Lesmes, Jackson, Wallis, & Bex, 2013).

6. Conclusion

6.1. Practical advice

Based on the considerations reviewed here, and our own experience in developing and using contrast sensitivity tests, we have five recommendations for contrast sensitivity testing.

1. FORCED CHOICE. Use a less-criterion-dependent objective test. This will minimize the effects of attitude, which vary and yet are not usually of interest in basic and clinical studies.
2. SCALE. When testing multiple sizes (or spatial frequencies), vary only size. Vision is roughly scale invariant and the test should be too, so that revealed scale dependence can be attributed directly to size and not any covarying test parameter.

3. MANY ALTERNATIVES. Use at least 4 or 5 alternatives to minimize the guessing rate to speed threshold estimation.
4. ADAPTIVE. If the test is not printed, then use an adaptive method, e.g. QUEST.
5. ONE OR MANY? If the test is printed, then think carefully about whether to show one or more letters at a time. Traditional charts show many letters, which saves space. However, if many letters or symbols are present, small children have trouble knowing which symbol is being tested, and some clinical groups, including central field loss, strabismic amblyopes, and apperceptive agnosics, may be affected by crowding (Levi, 2008; Pelli & Tillman, 2008). If using a computer, then just show one letter or symbol at a time.

Disclosure

Denis Pelli receives a small royalty from sales of the Pelli-Robson Contrast Sensitivity Chart. Peter Bex is co-inventor on a provisional USA patent "Rapid Measurement of Visual Sensitivity," and owns equity in Adaptive Sensory Technology LLC, which plans to license this patent and commercialize a rapid CSF test.

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