Vision Research 90 (2013) 10–14

Contents lists available at SciVerse ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Measuring contrast sensitivity

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ARTICLE INFO

Article history:
Received 13 February 2013
Received in revised form 24 April 2013
Accepted 25 April 2013
Available online 3 May 2013

Keywords:
Contrast sensitivity
Threshold
QUEST
Adaptive threshold estimation
Fechner

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 $L_{\max}$, $L_{\min}$, $L_{\mathrm{background}}$, 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/m^2) (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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http://dx.doi.org/10.1016/j.visres.2013.04.015

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).

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