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The slope of the psychometric function and non-stationarity of thresholds in spatiotemporal contrast vision

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ABSTRACT

The slope of the two-interval, forced-choice psychometric function (e.g. the Weibull parameter, β) provides valuable information about the relationship between contrast sensitivity and signal strength. However, little is known about how or whether β varies with stimulus parameters such as spatiotemporal frequency and stimulus size and shape. A second unresolved issue concerns the best way to estimate the slope of the psychometric function. For example, if an observer is non-stationary (e.g. their threshold drifts between experimental sessions), β will be underestimated if curve fitting is performed after collapsing the data across experimental sessions. We measured psychometric functions for 2 experienced observers for 14 different spatiotemporal configurations of pulsed or flickering grating patches and bars on each of 8 days. We found $\beta \approx 3$ to be fairly constant across almost all conditions, consistent with a fixed nonlinear contrast transducer and/or a constant level of intrinsic stimulus uncertainty (e.g. a square law transducer and a low level of intrinsic uncertainty). Our analysis showed that estimating a single β from results averaged over several experimental sessions was slightly more accurate than averaging multiple estimates from several experimental sessions. However, the small levels of non-stationarity (SD $\approx$ 0.8 dB) meant that the difference between the estimates was, in practice, negligible.

1. Introduction

Most studies of spatiotemporal contrast vision involve measuring the observer's psychometric function: a measure of performance (d' or percent correct) as a function of contrast. This is usually done using a two-interval, forced-choice method (2IFC). The lateral position of the psychometric function is an indication of an observer's sensitivity to the stimulus and the contrast associated with a particular—often arbitrary—performance level (e.g. 75% correct) is sometimes referred to as a 'threshold' (though authors do not always wish to invoke the theoretical concept that this implies). Sometimes, the experimenter is also interested in how performance varies with signal strength. This involves measuring the *slope* of the psychometric function. When the results are plotted as d' against contrast, on log–log axes, then the psychometric function is approximately a straight line (e.g. Pelli, 1985) and the slope of the psychometric function is given by the gradient of this line (b). When the performance measure is 'percent correct', plotted against log(contrast), then the psychometric function is sigmoidal (S-shaped) in form and often fitted by a Weibull function, for which the slope is given by its β parameter (see results section for details). To fair approximations, $\beta = 1.3b$ (Tyler & Chen, 2000) or $\beta = 1.247b$ (Pelli, 1987). The slope parameter is of interest to experimenters because it can be used to estimate the form of the observer's internal signal transducer (Nachmias & Sansbury, 1974) (e.g. linear vs. an accelerating square law), assuming no signal uncertainty (Foley & Legge, 1981; Lu & Dosher, 2008); the level of signal uncertainty (Lasley & Cohn, 1981), assuming a linear transducer (Georgeson, Yates, & Schofield, 2008; Pelli, 1985; Tyler & Chen, 2000); or some combination of the two (Meese & Summers, 2009). Note that if the contrast transducer (r) has the form $r = k \cdot c^p$, where c is stimulus contrast and k is a constant, then in the absence of uncertainty, $b = p$.

The slope parameter is also of interest in contrast discrimination experiments, where very low pedestal levels produce steeper psychometric functions than higher pedestal levels (Bird, Henning, & Wichmann, 2002; Meese, Georgeson, & Baker, 2006). Similarly, contrast detection of target in noise can show a similar increase in slope as the spectral density of the noise decreases (Legge, Kersten, & Burgess, 1987; though see Baker & Meese, 2012). Changes in single interval psychometric slope have been used to inform models of decision-making (e.g. Wang, 2002), perceptual learning (e.g. Gold et al., 2010) and attention (e.g. Cameron, Tai, & Carrasco, 2002). The slope of the psychometric function is also of interest in studies that measure a point of subjective equality and use the slope as a measure of discriminability, as is often done in work on cue combination (e.g. Ernst & Banks, 2002). However, to

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maintain focus, we restrict ourselves here to the study of the 2IFC psychometric function for contrast detection (a form of the psychometric function whose lower asymptote is 50% correct).

1.1. Five unanswered questions about the slope of the 2IFC psychometric function

In spite of growing theoretical interest in the slope of the 2IFC psychometric function (e.g. García-Perez & Alcala-Quintana, 2007; Lu & Dosher, 2008; Meese, Georgeson, & Baker, 2006; Meese & Summers, 2009; Petrov, Verghese, & McKee, 2006) few studies have provided a systematic empirical investigation of this parameter. The most obvious exception is a study by Mayer and Tyler (1986). Those authors measured thresholds and slopes (β) for 500 ms presentations of curved strips of grating for a wide range of sizes (4–48 grating cycles at 12 c/deg) and spatial frequencies (2–26 c/deg for 4 deg patches). Both of these manipulations were performed for gratings placed 3.5 deg into the periphery but only the spatial frequency manipulation was performed when the gratings were centred on the fovea. Mayer and Tyler reported some variation in β across their four observers but found no evidence for variation in β as functions of stimulus size or spatial frequency. On average, they found $\beta = 3.7$ for foveal viewing. Although broad in its scope, this study leaves several questions unanswered. In order of increasing priority these are:

1. Are similar results found using smoothly windowed stimuli such as Gabor patches (here we used log-Gabor stimuli) instead of hard-edged gratings? Although a fairly low-priority question, it is possible that performance in the Mayer & Tyler study was influenced by the high spatial frequency artefacts introduced by the hard-edged windowing of their stimuli.
2. Does the slope of the 2IFC psychometric function vary with stimulus size for foveal viewing? This has theoretical importance for understanding the processes of spatial summation (Tyler & Chen, 2000; see Summers and Meese (2007) for a preliminary report). Some of the conditions in the present study bear on this issue.
3. Does the slope of the 2IFC psychometric function change when the number of cycles is reduced below 4 (the lower limit used by Mayer and Tyler (1986))? The preliminary cortical filtering stage probably involves receptive fields that respond to fewer than four grating cycles (Meese, 2010) whereas larger gratings are detected by either probability summation amongst multiple mechanisms (Robson & Graham, 1981) or higher-order mechanisms performing spatial pooling (Meese, 2010). An argument has been made for the slope of the psychometric function to be affected by probability summation (Wilson & Bergen, 1979; see also Mayer & Tyler, 1986) and it is plausible that the contrast response characteristic of higher-order pooling mechanisms might be different from that of their lower-order feeder units, as in the case of a cascade of accelerating contrast transducers (Meese & Baker, 2011; Sclar, Maunsell, & Lennie, 1990). Therefore, the slope of the psychometric function might be informative about the transition from a single (or few) mechanisms to many. More generally, localised stimulus patches containing few stimulus cycles have become the preferred contrast stimulus in vision science (e.g. see the ModelFest project: Watson & Ahumada, 2005) and a study of the slope of the psychometric function for these stimuli is long overdue.
4. Is the slope of the 2IFC psychometric function the same or different for light bars and dark bars? There is evidence from psychophysics that luminance increments and decrements can have different thresholds (e.g. Krauskopf, 1980; Short, 1966) and evidence from retinal anatomy and single-cell physiology that ON and OFF sub-systems in the retina are very distinct both structurally and functionally (e.g. Balasubramanian & Sterling, 2009; Burkhardt, 2011; Field & Chichilnisky, 2007). We asked whether such differences might be reflected in the threshold or slope of the psychometric function.
5. Is the slope of the 2IFC psychometric function the same or different in the two opposite 'speed' corners of spatiotemporal vision? It is thought that the high-speed[1] corner of spatiotemporal vision (high temporal frequency, low spatial frequency) is dominated by the magnocellular pathway and that the slow-speed corner of spatiotemporal vision (low temporal frequency, high spatial frequency) is dominated by the parvocellular pathway (Merigan, Katz, & Maunsell, 1991; Merigan & Maunsell, 1990). The contrast responses of P-cells in the retina and lateral geniculate nucleus are far more linear than their M-cell counterparts, which first accelerate with contrast and then saturate (Croner & Kaplan, 1995; Shapley & Perry, 1986). Therefore, if psychophysical performance is determined by mechanisms with similar characteristics to the P- and M-streams, we should expect the slope of the psychometric function to increase with stimulus speed consistent with an increase in the underlying contrast response exponent (p; see above).

1.2. The issue of non-stationarity

There was one other important motivation for our study. The literature on sequential dependencies of observer responses (e.g. Howarth & Bulmer, 1956; Treisman & Williams, 1984) and perceptual learning (e.g. Gold et al., 2010) suggests that sensitivity can vary across repeated measures, implying that the observer's 2IFC psychometric function is not stationary but slides along the contrast axis over time. Few studies have investigated this systematically, though there is some evidence for such variations from an early study using a now obsolete methodology (Hallett, 1969). If the psychometric function is non-stationary, this has potentially important implications for its measurement (Frund, Haenel, & Wichmann, 2011). When data are gathered from multiple experimental sessions (blocks), often spread over several days, there are two main ways in which investigators proceed. Data are either (i) collapsed across multiple sessions and a single fit performed to estimate threshold and slope (the 'pool-then-fit' method), or (ii) fitted separately for each session, and threshold and slope derived by averaging the multiple estimates (the 'fit-then-pool' method). The pool-then-fit method has the advantage of lessening the effects of binomial error inherent in the data because the fits are made to larger data sets. However, it has the disadvantage that the slope of the psychometric function will be underestimated if the observer is non-stationary, because it involves pooling multiple psychometric functions with different thresholds.

1.3. Aims and outcomes

To address the five questions posed above and the issue of non-stationarity, we measured the psychometric function for a large set of widely varying spatiotemporal stimuli and repeated this several times over several days. We analysed our results using both the pool-then-fit method and the fit-then-pool method. We found no systematic effect of stimulus type on the slope of the psychometric function (with only one exception) but did find low levels of non-stationarity. However, the amount of non-stationarity was so small that it had little impact on our estimates of pool-then-fit slopes, whereas the fit-then-pool slopes were slightly over-estimated, due to undersampling. Thus—for well-practised observers at

[1] When we use the term 'speed' we refer to the scalar quantity given by dividing temporal frequency by spatial frequency. We do not imply that the stimulus is drifting.