

Accuracy of identification of grating contrast by human observers: Bayesian models of V1 contrast processing show correspondence between discrimination and identification performance

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Received 16 July 2004; received in revised form 6 June 2005

Abstract

This paper presents the results of a contrast identification study, where accuracy in identification is quantified as mutual information between stimulus contrast and observer's response. The stimulus was a set of 2–8 gratings, spanning the range of visible contrasts. Gratings from the set were presented individually for 500 ms, and the observer had to respond by giving the number label corresponding to the contrast of the grating presented. Mutual information increased with set size up to a maximum of around 2.35 bits, i.e., only 5 clearly identifiable contrasts. Set sizes greater than 5 showed a plateau or decline in performance. These data were well fit by Bayesian models of V1 contrast coding, with the parameters obtained by fitting the contrast discrimination results of Chirimuuta and Tolhurst [Chirimuuta, M., & Tolhurst, D. J. (2005). Does a Bayesian model of V1 contrast coding offer a neurophysiological account of human contrast discrimination? *Vision Research*].

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Keywords: Contrast coding; Information; Information theory; Bayesian model; Identification; Psychophysics; V1; Contrast

1. Introduction

The way in which human observers perceive different contrasts of sinusoidal gratings is conventionally investigated by measuring the thresholds for *detecting* gratings or for *discriminating the contrasts* of gratings (seminally: Foley, 1994; Legge & Foley, 1980). A typical 2AFC *contrast discrimination* experiment requires the observer to indicate which of two paired stimuli has the higher contrast. One result of such experiments is the demonstration of the “dipper function” for contrast discrimination, with Weber-like behaviour at clear suprathreshold contrasts (Campbell & Kulikowski, 1966; Itti, Koch, & Braun, 2000; Legge, 1981; Nachmias & Sansbury, 1974; Tolhurst

& Barfield, 1978). The minimum contrast discrimination threshold is around 40–50 dB (0.3–1.0%) depending, for instance, on the size and spatial frequency of the stimulus used. The dipper function is also found with natural-scene stimuli (Chirimuuta & Tolhurst, 2004). Its form has been variously explained as being due to a sigmoidal response-contrast or transducer function (Boynton, Demb, Glover, & Heeger, 1999; Legge & Foley, 1980; Nachmias & Sansbury, 1974; Stromeyer & Klein, 1974), to increasing response variance at high contrasts (Itti et al., 2000), or to a combination of those two added to the uneven distribution of the dynamic ranges of populations of V1 neurons each with limited dynamic range (Chirimuuta & Tolhurst, 2005).

Discrimination experiments have been augmented by *contrast matching* experiments where, for instance, gratings of different spatial frequency or different mean luminance are adjusted until they *appear* to the observer

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to be of the same contrast (e.g., Blakemore, Muncey, & Ridely, 1973; Cannon & Fullenkamp, 1988, 1993, 1996; Georgeson, 1991; Georgeson & Sullivan, 1975; McCourt & Blakeslee, 1994; Peli, Yang, & Goldstein, 1991; Snowden & Hammett, 1998). Discrimination and matching studies both rely upon explicit comparisons between pairs of stimuli, and a detection task requires implicit comparison with a “blank” display. An alternative psychophysical approach is to present just a single stimulus and to ask an observer to rate it on some “internal”, subjective but consistent scale. In such experiments, the observer must indicate the absolute value of a stimulus property rather than a comparative one. The property may be a continuous one such as contrast. The absolute identification experimental paradigm and method of analysis were first employed by Garner and Hake (1951) in an experiment in which observers had to make absolute judgements of the loudness of sounds. Since then, the paradigm has been used psychophysically in other sensory modalities, such as taste (e.g., judgements of sweetness intensity, Schifferstein & Frijters, 1992). It has been adapted to the study of contrast perception by Gottesman, Rubin, and Legge (1981), Brannan and Bodiswollner (1991) and Peli et al. (1991), and, in a related form, by Kulikowski (1976).

A *contrast identification* experiment requires the observer to state the contrast level of a single stimulus without explicit comparison with other stimuli. Results might be tabulated as a “stimulus–response matrix” (Sagi, Wong, & Norwich, 2001) and one approach would be to calculate the *mutual information* between stimulus contrasts and the observer’s responses, as a measure of the accuracy with which the observer can identify and name the stimuli. A great attraction of such an approach is that it is exactly analogous to one favoured approach of neurophysiologists, who can easily examine the relation between response amplitude in single sensory neurons and stimulus intensity. For instance, the approach has been used to measure the information transmitted by monkey mechanoreceptive afferent neurons (Werner & Mountcastle, 1965), by cat muscle spindle afferents (Matthews & Stein, 1969), and by neurons in cat visual cortex (Tolhurst, 1989). In general, any one mammalian sensory neuron seems capable of transmitting rather little information (0.5–2 bits) about sensory intensity.

Indeed, it is the ease with which an information-theoretic approach can be applied to study both the invertebrate (e.g., de Ruyter van Steveninck & Laughlin, 1996; Juusola & de Polavieja, 2003; Laughlin, 1981; Rieke, Warland, de Ruyter van Steveninck, & Bialek, 1999) and the mammalian visual system (Optican & Richmond, 1987; Reich, Mechler, Purpura, & Victor, 2000; Reinagel, Godwin, Sherman, & Koch, 1999; Tolhurst, 1989; Wiener, Oram, Liu, & Richmond, 2001) at the single-neuron level that makes it attractive to try to apply

an analogous approach in a psychophysical paradigm, in order to compare neuronal and behavioural measures directly.

In this paper, we present the results of psychophysical contrast identification experiments, to document how much information a human observer receives about grating contrast. We then present a computational simulation of how populations of primary visual cortex (V1) neurons might behave in such an experiment, and we compare the model predictions with the experimental data. Neurophysiological (Geisler & Albrecht, 1997) and functional imaging (Boynton et al., 1999; Haynes, Roth, Stadler, & Heinze, 2003; Ress & Heeger, 2003) evidence suggests that V1 is a brain area critical for contrast identification. Our model of contrast identification, therefore, simulates the noisy contrast-response functions of groups of monkey V1 neurons, and performs a Bayesian analysis of the statistics of these responses (Chirimuuta, Clatworthy, & Tolhurst, 2003; Chirimuuta & Tolhurst, 2005; Clatworthy, Chirimuuta, Lauritzen, & Tolhurst, 2003). This allows us to estimate the accuracy with which populations of model neurons might identify contrasts across the same range tested psychophysically. The estimated *mutual information* between contrast stimuli and neuronal responses will be compared with the psychophysical results. In particular, we will examine whether the model is consistent with the psychophysical accuracy results, when the parameters of the model are set, as in the accompanying paper (Chirimuuta & Tolhurst, 2005), to best explain the form of the contrast discrimination dipper. Some of these results have been reported briefly (Tolhurst & Chirimuuta, 2004).

2. Methods

2.1. Apparatus

Grey-level stimuli were presented on a SONY 19” colour monitor driven by a VSG 2/4 graphics card (Cambridge Research Systems). Observers sat in a dimly lit room at a distance of 2.28 m from the screen, which was 9.25 deg (37 cm) wide \times 7 deg (28 cm) high. Viewing was binocular, with free fixation. The screen had a space-averaged mean luminance of 44 cd m⁻², bright enough to be in the photopic range.

2.2. Stimuli

The stimuli were mostly vertical, 2.67 c deg⁻¹ sinusoidal gratings and Gabor patches. These were all calculated as 256 \times 256 pixels (where pixel size was 1.44’), represented to 256 grey levels, giving a maximal image size of 24 cm \times 24 cm (6 deg \times 6 deg at the viewing distance). The VSG 2/4 had “pseudo-15-bit” control of pixel luminance (Pelli & Zhang, 1991); this allowed

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