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Fixed versus variable internal noise in contrast transduction: The significance of Whittle's data

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ABSTRACT

A longstanding issue in vision research concerns whether the internal noise involved in contrast transduction is fixed or variable in relation to contrast magnitude. Previous attempts to resolve the issue have focused on the analysis of contrast discrimination data, despite the fact that the effects of internal noise on thresholds are necessarily compounded by the shape of the underlying transducer function. An alternative approach is to compare data obtained from a particular class of scaling experiment – one based on a comparison of perceived contrast differences – with data from discrimination experiments gathered across the full range of contrast. Data from two studies by the late Paul Whittle provide the basis for such an analysis, pointing to the conclusion that contrast internal noise is fixed not variable.

1. Introduction

The perception of image contrast is fundamental to vision. One issue that continues to engage the vision community is whether the internal noise associated with contrast transduction is best modelled as fixed or variable in relation to contrast magnitude (Garcia-Pérez & Alcalá-Quintana, 2009; Georgeson & Meese, 2006; Gorea & Sagi, 2001; Goris, Putzeys, Wagemans, & Wichmann, 2013; Goris, Zaenen, & Wagemans, 2008; Katkov, Tsodyks, & Sagi, 2006a, 2006b; Klein, 2006; Kontsevich, Chen, & Tyler, 2002; Kontsevich, Chen, Verghese, & Tyler, 2002; Solomon, 2007a, 2007b; Swets, Tanner, & Birdsall, 1961; Wichmann, 1999). The term 'additive' is sometimes used instead of fixed, and one form of variable noise is 'multiplicative', meaning that internal noise increases proportionately with contrast (e.g. Klein, 2006; McIlhagga & Peterson, 2006). Thus the issue is sometimes framed as that between additive and multiplicative internal noise.

Contrast discrimination experiments typically measure contrast increment thresholds, or JNDs (just-noticeable-differences) as a function of baseline, or 'pedestal' contrast. Since increment thresholds are limited by internal noise, attempts to determine how internal noise grows with contrast have understandably focused on the analysis of contrast discrimination behavior. The challenge stems from the fact that contrast increment thresholds are determined not only by internal noise but also by the shape of the function that maps physical contrast onto its internal representation – the so-called "transducer function". As Georgeson and Meese (2006) put it, determining whether contrast internal noise is fixed or variable is an elusive goal, because performance depends on the signal-to-noise ratio, and so it is not easy to disentangle the separate dependences of signal and noise on contrast. Fig. 1 illustrates the problem by showing how a compressive transducer function with additive noise can result in the same pattern of JNDs as a linear transducer function with multiplicative noise. Noteworthy in this regard is Fechner's famous integration of Weber's Law to derive the shape of the underlying transducer function (Fechner, 1860/1966). Fechner hypothesised that sensitivity to changes in stimulus intensity was proportional to the rate of apparent stimulus change. However as Fig. 1 shows, this will only be true if internal noise is fixed.

Various methods have been proposed for deciding between fixed and variable noise using discrimination data. Gorea and Sagi (2001) used a "dual-pedestal" paradigm in the context of a signal-detection-theory analysis. On each trial of a Yes/No task observers were required to simultaneously monitor two pedestals with different contrasts, either of which might contain the test contrast increment. They assumed that subjects adopted the same

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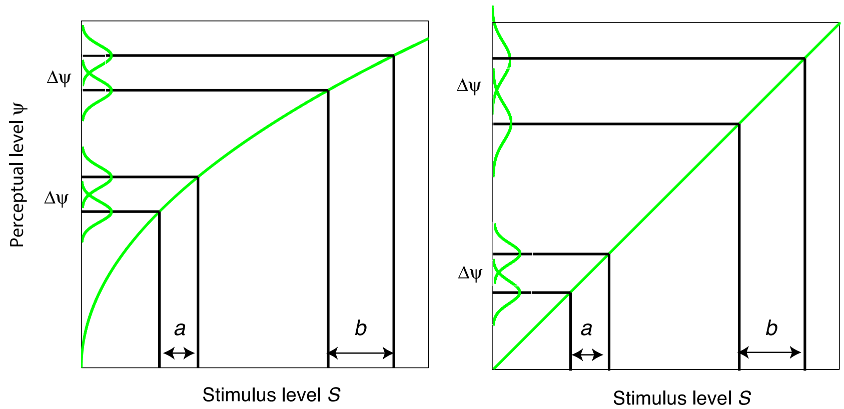

Fig. 1. Hypothetical transducer functions showing the relationship between perceptual level and stimulus level or intensity. Left: a compressive transducer function with fixed, or 'additive' internal noise. Right: a linear transducer with variable, specifically multiplicative internal noise. Each graph shows two pairs of stimulus levels, each pair separated by a JND. The corresponding perceptual levels are the mean levels of Gaussian noise distributions, with the separation in each pair set to equal signal-to-noise ratios. Note that the size of the JNDs given by a and b are the same in both figures.

criterion – termed the "unique criterion constraint" - for detecting the contrast increment on either pedestal. Under this assumption Gorea and Sagi showed via a signal detection analysis that the relative standard deviations of the internal noise levels of the two pedestals was given by the relative false-alarm rates of the corresponding pedestal + test conditions. They found similar false-alarm rates across a range of pedestal contrasts and concluded that internal contrast noise is therefore fixed not variable. However, in a critique of Gorea and Sagi (2001), Kontsevich, Chen, Verghese et al. (2002) argued that the assumption of a unique criterion constraint in the dual-pedestal paradigm was unjustified, and so too therefore was Gorea and Sagi's conclusion that internal noise was fixed.

A different method based on signal detection theory was employed by Solomon (2007b). He used a protocol first described by Swets et al. (1961), termed the "second-response paradigm". In forced-choice tasks with more than two alternatives one can require observers to provide both first and second choices as to the alternative containing the target. According to Solomon (2007a, 2007b) the conditional probability of a correct second response given an incorrect first response is independent of the shape of the transducer, but dependent on whether the internal noise is fixed or variable. Using a 4-AFC Gabor detection task, Solomon (2007b) showed that the predicted conditional second response probability was consistent with a slowly increasing, i.e. variable internal noise level with pedestal contrast.

Most studies addressing the fixed vs. variable internal noise issue have concentrated on fitting models to psychometric function data obtained from conventional 2AFC contrast discrimination tasks. In many cases the focus is on the 'dipper' region of the threshold vs. pedestal function, i.e. the low contrast pedestal region where test thresholds are lower in the presence of compared to absence of the pedestal. Some of these studies have come out in support a fixed noise model (Katkov et al., 2006a, 2006b; and for sustained stimuli Wichmann, 1999, as cited in Georgeson & Meese, 2006), but more often a variable noise model (Goris et al., 2008, 2013; Klein, 2006; Kontsevich, Chen, Tyler et al., 2002; Nachmias & Kocher, 1970; and for brief test durations Wichmann, 1999, as cited in Georgeson & Meese, 2006). It is also worth noting that many models of contrast discrimination behavior *assume* fixed noise (e.g. Legge & Foley, 1980; Meese, Georgeson, & Baker, 2006; Stromeyer & Klein, 1974).

I mention the above contrast discrimination studies not as a prelude to their detailed examination but to draw attention to the fact that there is a lack of consensus among them as to whether internal contrast noise is fixed or variable. Moreover, the conclusions of some of the above studies have been called into question: when Kontsevich, Chen, Tyler et al.'s (2002) data, which were used to support a variable noise model, were re-examined by Georgeson and Meese (2006), a fixed noise model was found to fare no worse. As if to put the nail into the coffin, Garcia-Pérez and Alcalá-Quintana's (2009) have argued that the fixed vs. variable noise issue simply cannot be solved by fitting models to contrast discrimination data. Thus to conclude, in the words of Georgeson and Meese (2006), the jury is "still out".

2. A different approach

The aim of this communication is not to evaluate previous attempts to disentangle fixed from variable contrast noise using discrimination data but to suggest an alternative approach, for which, fortuitously, data already exists. The data comes from two studies by the late Paul Whittle, one dealing with brightness discrimination (Whittle, 1986), the other brightness scaling (Whittle, 1992; both studies summarized in Whittle, 1994). Interestingly, Whittle never considered the significance of his data in terms of the fixed vs. variable noise issue. Rather, he aimed to derive a general formula for relating brightness (he used the term "contrast brightness") to luminance for both incremental and decremental disks, on different intensities of background, and for three types of perceptual task: matching, discrimination and scaling.

The proposal here (briefly reported in Kingdom, 2009) is that one can estimate how internal contrast noise varies with contrast by comparing the results from two types of experiment: scaling and discrimination. Scaling experiments attempt to derive directly the relationship between the perceived and physical properties of a stimulus dimension, and are generally measured using appearance-based tasks (for a review see Kingdom & Prins, 2016). On the other hand discrimination experiments that measure JNDs are performance-based. As noted above, it is the results from discrimination experiments that have been primarily employed to address the fixed vs. variable noise issue. How then might scaling experiments, in combination with discrimination experiments, help resolve the issue? To answer this question it is first useful to distinguish between two types of scaling experiments: those that measure relative perceived magnitudes and those that measure relative perceived magnitude *differences*, the latter termed here 'difference-scaling' experiments. Scaling experiments that measure relative perceived magnitudes, such as the method of paired comparisons, typically require observers to compare the magnitudes of a single pair of stimuli. On the other hand, difference-scaling experiments, such as Maximum Likelihood Difference Scaling (Maloney & Yang, 2003), require observers to