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Individual differences in internal noise are consistent across two measurement techniques

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ABSTRACT

Internal noise is a fundamental limiting property on visual processing. Internal noise has previously been estimated with the equivalent noise paradigm using broadband white noise masks and assuming a linear model. However, in addition to introducing noise into the detecting channel, white noise masks can suppress neural signals, and the linear model does not satisfactorily explain data from other paradigms. Here we propose estimating internal noise from a nonlinear gain control model fitted to contrast discrimination data. This method, and noise estimates from the equivalent noise paradigm, are compared to a direct psychophysical measure of noise (double-pass consistency) using a detailed dataset with seven observers. Additionally, contrast discrimination and double-pass paradigms were further examined with a refined set of conditions in 40 observers. We demonstrate that the gain control model produces more accurate double-pass consistency predictions than a linear model. We also show that the noise parameter is strongly related to consistency scores whereas the gain control parameter is not; a differentiation of which the equivalent noise paradigm is not capable. Lastly, we argue that both the contrast discrimination and the double-pass paradigms are sensitive measures of internal noise that can be used in the study of individual differences.

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1. Introduction

Internal noise is intrinsic to the assumptions of signal detection theory (Green & Swets, 1974; Macmillan & Creelman, 2005) and signal degradation due to internal variability is evident in both electronic systems (e.g. amplifiers) and living organisms. Neural internal noise is inherent to sensory neurons and acts as a limiting factor in signal transduction (Faisal, Selen, & Wolpert, 2008). In psychophysics, this leads to the psychometric function taking the shape of a sigmoid rather than transitioning sharply between sub-threshold and supra-threshold stimuli (Burgess & Colborne, 1988). A substantial body of research has attempted to measure noise psychophysically for many different visual cues, including luminance (Barlow, 1956), orientation (Jones, Anderson, & Murphy, 2003), shape (Sweeny, Grabowecky, Kim, & Suzuki, 2011), motion perception (Barlow & Tripathy, 1997) and contrast (Burgess & Colborne, 1988; Lu & Dosher, 2008; Pelli, 1985).

Differences in internal noise have been reported in normal human development (Skoczenski & Norcia, 1998) and ageing (Pardhan, 2004) and in clinical conditions such as amblyopia (Levi, Klein, & Chen, 2007), macular degeneration (McAnany, Alexander, Genead, & Fishman, 2013) and autism (Dinstein et al., 2012; Milne, 2011). Furthermore, individual differences in contrast sensitivity for neurotypical adults have also been explained as being partly due to noise (Baker, 2013). In order to assess differences in internal noise levels between observers it is crucial to use a paradigm that is capable of distinguishing internal noise effects from other performance-influencing factors (such as sensitivity, suppression, uncertainty or efficiency). We now discuss several candidate psychophysical methods that might be used to achieve this aim.

1.1. Equivalent noise

Most commonly, the influence of internal noise on psychophysical task performance is assessed by purposefully degrading the performance of the observer by presenting external stimulus noise (such as 2D isotropic white noise; Pelli, 1985). The most widely adopted method is the equivalent noise (EN) paradigm (Legge, Kersten, & Burgess, 1987; Pelli, 1985) in which observers perform a two-alternative-forced-choice (2AFC) detection experiment with white noise masks shown in both intervals and a target stimulus added to one. Detection thresholds are obtained for several mask

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contrast levels, and the mask noise level at which performance begins to decline is taken as an estimate of the amount of internal noise in the system.

The EN paradigm assumes a linear amplifier model (Pelli, 1985), that defines thresholds as:

$$C_{thresh} = \frac{\sqrt{2\sigma_{ext}^2 + 2\sigma_{int}^2}}{\beta} \quad (1)$$

where C_{thresh} is the threshold target contrast level, β is a parameter reflecting efficiency (Lu & Dosher, 2008) and σ_{ext} and σ_{int} are the levels of external (stimulus) noise and internal noise respectively. The model posits a linear relationship between stimulus input and signal output, with additive internal noise. External stimulus noise introduces variability into the detecting mechanism that impairs performance at high noise contrasts (when $\sigma_{ext} > \sigma_{int}$).

However, there is abundant evidence that the relationship between stimulus contrast and visual response is not linear but rather accelerating at low contrasts and saturating at high contrasts (Baker, 2013; Boynton, Demb, Glover, & Heeger, 1999; Legge & Foley, 1980; Tsai, Wade, & Norcia, 2012). Furthermore, due to the broad frequency and orientation profile of white noise masks, non-target channels will also be activated by the mask and in turn inhibit the target channel. It has recently been demonstrated that broadband white noise has a strong suppressive effect similar to that of narrowband cross-oriented masks (Baker & Vilidaite, 2014). This suggests that impaired performance at high mask contrasts in the EN paradigm could be due to cross-channel suppression from white noise rather than within-target-channel noise (Baker & Meese, 2012).

One potential solution to this is to inject variability only to the detecting channel tuned to the target. This is possible by removing from the mask all off-channel spatial frequency and orientation information. The result is a mask that is spatially identical to the target grating, but with a randomly selected contrast – a 'zero-dimensional' (0D) noise mask (Baker, 2012). Similar approaches have been previously used in luminance (Cohn, 1976), orientation (Dakin, Bex, Cass, & Watt, 2009) and auditory tone perception (Jones, Moore, Amitay, & Shub, 2013). The contrast level of the mask is randomly sampled from a Gaussian distribution to create interval-by-interval contrast jitter. It has been shown that this type of mask produces stronger masking effects than white noise (Baker, 2012, 2013), and does not show evidence of cross-channel suppression, so it may offer a more suitable alternative to white noise masks.

However, it has been pointed out (Allard & Faubert, 2013) that zero-dimensional noise masks tend to produce near perfect efficiency, implying that estimates of internal noise using this paradigm are determined entirely by detection thresholds in the absence of a noise mask! In addition, the EN paradigm still assumes a linear model that is at odds with contemporary accounts of contrast transduction (e.g. Baldwin, Baker, & Hess, 2016). In order to take into account the nonlinearity of the human visual system, paradigms and models that have more accurate underlying assumptions must be considered.

1.2. Pedestal masking

One possible alternative to the equivalent noise approach is to obtain an estimate of internal noise by measuring and modelling discrimination data. This type of noise estimate has been used in auditory research where the fitted noise parameter was shown to be a good predictor of other measures of internal noise in the auditory system (Buss, Hall, & Grose, 2009; Jones et al., 2013). The same method can be implemented in visual contrast discrimination (Baker, 2013; Baldwin et al., 2016). In this paradigm, a fixed contrast pedestal stimulus is presented in both intervals of a 2AFC experiment with a target contrast increment added to one of the intervals. A staircase procedure is used to obtain discrimination thresholds at several pedestal contrast levels. The resulting function takes the shape of a dipper (Nachmias & Sansbury, 1974), with a facilitatory effect at low pedestal levels and threshold elevation from masking at higher levels of pedestal contrast. The contrast response function underlying the dipper (e.g. Boynton et al., 1999) is well described by a transducer nonlinearity (Legge & Foley, 1980; Tsai et al., 2012) adapted from the Naka-Rushton equation (Naka & Rushton, 1966):

$$resp = \frac{C^p}{Z + C^q} + \sigma_{int} \quad (2)$$

where C is the stimulus contrast, p and q are exponents that produce an accelerating response across low contrasts and a compressive response across high contrasts, Z is the saturation constant (the gain control parameter) and σ_{int} is proportional to the participant's internal noise. To simulate contrast discrimination experiments, a response (*resp*) is generated for each of the two intervals (with zero mean Gaussian noise added to each), and the interval with the larger response is selected. The influences of gain control and internal noise can be differentiated (see Fig. 1): increasing the gain control parameter (Z) elevates thresholds only at low pedestal levels, whereas changing the noise parameter (σ_{int}) shifts the function vertically at all pedestal contrasts. Fitting the model to empirical contrast discrimination data will therefore provide an estimate of internal noise that is decoupled from estimates of sensitivity (or gain). However, it is currently unknown how accurate noise estimates using this method are, so it would be useful to compare it to a more direct measure.

1.3. Double-pass consistency

When there is no variability in the stimulus, most variability in an observer's responses must be due to internal noise. One way of way estimating internal noise, therefore, is to present a sequence of noisy stimuli multiple times and look at the consistency of responses across repetitions. This method is considered to be a direct way of measuring internal noise (Burgess & Colborne, 1988; Lu & Dosher, 2008), and is typically performed with two passes (and referred to as the double pass method). Double-pass methods are well established both in auditory (Green, 1964; Jones et al., 2013) and visual modalities (Burgess & Colborne,

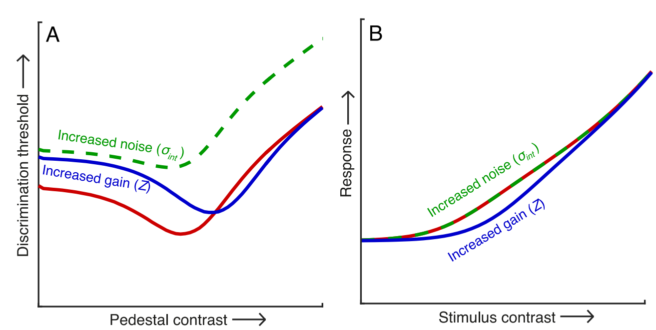

Fig. 1. Panel A. Model predictions for contrast discrimination with different model parameters. The red curve shows a typical dipper function for reference (parameter values: $\sigma_{int} = 0.2$, $Z = 8$); the green curve shows the vertical shift of the whole dipper function when the noise parameter (σ_{int}) is increased by a factor of 3.5; and the blue curve shows the diagonal shift of the function when the gain control parameter (Z) is increased by a factor of 4 (at low pedestal contrasts thresholds increase, but the dipper handles converge at high contrasts). Panel B. Corresponding contrast response curves. Red and green lines here overlap showing that changes in σ_{int} do not produce a shift in the function whereas an increase in Z produces a rightward shift. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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