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Individual differences in visual science: What can be learned and what is good experimental practice?

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ABSTRACT

We all pass out our lives in private perceptual worlds. The differences in our sensory and perceptual experiences often go unnoticed until there emerges a variation (such as 'The Dress') that is large enough to generate different descriptions in the coarse coinage of our shared language. In this essay, we illustrate how individual differences contribute to a richer understanding of visual perception, but we also indicate some potential pitfalls that face the investigator who ventures into the field.

1. Introduction

Visual science continues to generate an enormous body of empirical data on the characteristics and mechanisms of visual processing. Most such studies are designed to test different observers under nominally the same conditions, to understand the effects of those conditions and their implications for underlying processes. Multiple observers are included to ensure that the results are general, for example, to confirm that the findings can be replicated with naïve observers who are unaware of the aims of the study. The use of multiple observers also ensures that the results are significant and reliable. The data from different observers provide the estimate of measurement error. In this regard, the differences between observers are treated as a nuisance factor to be ignored – as mere noise in the measurements. And in very many studies these differences have accordingly lain unexploited.

However, the patterns of variations between observers are often systematic, and often arise from real differences in the very optical, neural, and cognitive processes that mediate the perceptions that the researchers are interested in. In this regard, individual differences provide a largely unmined treasure trove of information about these processes (de-Wit & Wagemans, 2016; Peterzell, 2016; Wilmer, 2008). Today, visual scientists have available to them extensive collections of archival data from recent times and from decades past. These data often include individual variability that is reported but left unexamined. Compared to many areas of experimental psychology, these psychophysical data can have very low measurement (intra-observer) error, and in many cases can be evaluated against precisely quantified properties or well-defined models of the visual system. They therefore promise powerful new insights. As new questions are pursued, there is also potential for experimental designs that yield richer information by exploiting inter-observer variation, and visual scientists are increasingly turning to studies focused on measuring and analysing the visual differences between observers.

Yet all datasets also include variations that are not of interest to the experimenter, that reflect random noise or introduce confounds unrelated to the tested hypotheses (see §5 below). These spurious variations may mask or impersonate the target of inquiry. As we discuss below, these confounds can be especially problematic in studies of individual differences. Thus investigators must mine individual variations cautiously, or they risk lining their pockets with fool's gold. We hope this review will both highlight the power of individual differences in vision research, and provide some prescriptions for best practices.

2. Differences between individuals

Individual differences can be defined and interpreted in a variety of

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ways. One important distinction is between 'individual differences *in data*', and '*true* individual differences'. The former phrase refers to differences obtained in actual measurements, and these can arise from real differences between individuals, but also from measurement error (e.g. from random variability, systematic biases, instrumental variation, and more). 'True individual differences' refers to variability that remains after the effect of measurement error has been excluded. It is a hypothetical construct, and an aspirational goal of measurement. In other definitions, 'true individual differences' involve more than zero measurement error, because they include only variability that is intrinsic to individuals, reflecting differences in a trait and not merely a state. As we discuss below, these distinctions are important for deciding how to design and interpret experiments probing observer differences.

When individuals who differ from others in a consistent way are categorized as a group, individual differences lead to group differences. Very many studies have investigated such group differences. Much of clinical vision is concerned with understanding disease by comparing control individuals to different patient populations; studies of development or lifespan compare individuals grouped by age; and studies on demographic factors might classify participants by gender or ethnicity. In designing these studies, individuals are often classified by predefined criteria, and results are then analysed in terms of the discrete groups. This has of course been a very fruitful approach, but can miss opportunities for a richer understanding of the observer differences because the within-group differences are again treated as noise. Research on true individual differences treats each observer as an individual. This can and often does still allow for observers to be classified by different criteria (e.g. according to their age or visual acuity), but importantly, also allows measurements to be analysed when the relevant classification is unknown (e.g. in the case of a set of observers all defined as 'normal' on some assessment).

The distinction between groups and individuals also has important implications for how a visual process is characterized or modelled. Colour science, and especially applied fields like colorimetry, rely heavily on the concept of a standard observer, defined by the average of the measurements for a large number of individuals. Similar models have been developed for other visual attributes such as spatial sensitivity (Watson & Ahumada, 2005). The standard observer provides an important working assumption for studying or predicting visual performance, but also has important limits, since it may rarely describe the properties of an actual observer. As we note below, for some applications the standard observer is of little value because it does not allow sufficient specification of the impact of the stimulus. Moreover, the mean alone provides no information on the range of tolerances that might be acceptable, say, to a given proportion of the population for an application like colour rendering. New observer models are being developed that explicitly incorporate estimates of normal variation in colour vision to better predict how a given individual or group might experience colour (Asano, Fairchild, & Blondé, 2016).

3. Sources of individual differences in vision

Variations in visual processing arise from many sources and are likely to be a prevalent characteristic at all levels of visual coding and all stages of the visual pathways. Even in the very first steps of image formation there are large, stable, and consequential variations in the optical aberrations of the eye, which affect the quality and form of the individual's idiosyncratic retinal image (Castejon-Mochon, Lopez-Gil, Benito, & Artal, 2002; Porter, Guirao, Cox, & Williams, 2001).

Colour vision is a case where patterns of individual differences have been extensively characterized (Webster, 2015b). The eye's optics differ in spectral quality, owing to pigment in the crystalline lens that screens light of shorter wavelengths. The density of the lens pigment varies markedly across observers and also increases steadily with age (Pokorny, Smith, & Lutze, 1987; Weale, 1988; Werner, 1982). Similarly, observers vary widely in the density of the macular pigment screening the central fovea (Bone & Sparrock, 1971; Werner, Donnelly, & Kliegl, 1987. These pre-receptoral filters strongly bias the spectrum of the light reaching the photoreceptors and are in fact the primary source of inter-observer variations in colour matching (Webster & MacLeod, 1988). Moreover, the spectral sensitivities of the cone photoreceptors vary reliably in the positions of their peaks (λ_{max}) (Winderickx et al., 1992) and in their bandwidths (e.g. because of variations in optical density) (Wyszecki & Stiles, 1980). As is well known from studies of colour deficiencies, there can also be large and diverse differences in both the number and nature of the cone types (Neitz & Neitz, 2011). Also, there are striking differences in the relative numbers of different cone types. For example, it is often noted that there are on average twice as many L cones as M cones in humans, yet in individuals with normal colour vision the ratio of L to M cones has been reported to vary from 1:1 to 16.5:1 (Hofer, Carroll, Neitz, Neitz, & Williams, 2005).

There are also large and reliable individual differences in subjective judgments of colour, i.e. in how colours are reported or categorized. The stimulus spectra that observers describe as unique hues (pure red, green, blue, or yellow), or that they experience as achromatic, vary widely from one observer to the next (Bosten, Beer, & MacLeod, 2015; Kuehni, 2004; Webster, Miyahara, Malkoc, & Raker, 2000b). Moreover, there are very large differences in the patterns of colour naming. Anthropological studies of colour naming have focused on cross-linguistic differences in order to understand the aetiology of colour categories and whether they are more strongly determined by universal (e.g. biological) or relative (e.g. cultural) processes (Kay & Regier, 2006). However, these analyses have tended to overlook the enormous variations in colour naming within a language. A re-examination of the World Colour Survey found that individuals varied widely in their patterns of colour naming and that these basic 'motifs' were often more similar across speakers from different languages than among members from the same linguistic group (Lindsey & Brown, 2009). Recent analyses have also pointed to the importance of characterizing individual differences for understanding the representation of colour in a culture. For example, some languages are characterized by few colour terms and high levels of uncertainty at the level of the individual, yet include a rich parcellation of colour at the level of the society (Lindsey, Brown, Brainard, & Apicella, 2015).

A further important source of variation in colour vision – and indeed all vision – is variation in the observer's environment. While natural visual environments have many characteristic properties that are thought to have shaped visual coding (Geisler & Ringach, 2009; Simoncelli & Olshausen, 2001), the world also varies across both space and time. For example, observers are exposed to very different colours in lush or arid environments, and colours in the same location can cycle with the seasons (Webster, Mizokami, & Webster, 2007; Webster & Mollon, 1997). Similarly, the diet of faces experienced by an individual varies widely depending on his or her social environment. Vision routinely adapts to the prevailing stimulus characteristics of the environment (Webster, 2015a). Potential examples of such contextual effects are seasonal changes in colour appearance (Welbourne, Morland, & Wade, 2015) or 'other-race' effects in the perception of faces (Meissner & Brigham, 2001).

As the forgoing examples suggest, the causes of individual differences in vision are many. Some can be highly stable and tied directly to genes. Others depend on lifestyle and experience. For example, age-related changes in lens pigment density are largely a consequence of exposure to light (Lindsey & Brown, 2002), while the density of macular pigment (consisting of the retinal carotenoids lutein and zeaxanthin) varies with the amount of carotenoids in the individual's diet (Hammond et al., 1997). The sources of differences can also be intricately intertwined. For instance, an indirect genetic effect on macular pigment density could arise if polymorphism of the taste receptors mediated differences in diet, leading to a knock-on effect on macular pigment and colour vision. Similarly, an individual's culture or profession will determine the distribution of colours or faces he or she is