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The structure of inter-individual differences in visual ability: Evidence from the general population and synaesthesia

Jamie Ward [a,b,*], Nicolas Rothen [c,d], Acer Chang [a,b], Ryota Kanai [a,b]

[a] School of Psychology, University of Sussex, Brighton, UK
[b] Sackler Centre for Consciousness Science, University of Sussex, Brighton, UK
[c] Institute of Psychology, University of Bern, Bern, Switzerland
[d] Center for Cognition, Learning and Memory, Bern, Switzerland

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ABSTRACT

This study considers how inter-individual differences in visual ability are structured. Visual ability could be a single entity (along the lines of general intelligence, or 'g'), or could be structured according to major anatomical or physiological pathways (dorsal v. ventral streams; magno- v. parvo-cellular systems); or may be a finer-grained mosaic of abilities. To test this, we employed seven visual psychophysical tests (generating 16 measures) on a large (100+) sample of neurotypical participants. A Varimax-rotated PCA (Principal Component Analysis) revealed a two-factor solution that broadly corresponds to a high and low spatial frequency division (consistent with a magno/parvo distinction). Over and above this, two measures (temporal order judgments; gain in contrast sensitivity) correlated with most others, and loaded on both factors, suggesting that they tap broad visual processing demands. These analyses open up further possibilities for exploring the genetic and neuroscientific foundations of differences in visual ability. The tests were also run on a group of individuals with different types of visually-based synaesthesia, given that previous research have suggested they possess a distinct profile of visual abilities. Synaesthesia was linked to enhanced processing of colour and shape/curvature information (amongst others), that may relate to differences in V4 in this group. In conclusion, individual differences in vision are both striking and meaningful, despite our difficulty to imagine seeing the world any differently.

1. Introduction

Aside from disorders of vision, normal individual differences in visual perception have been relatively neglected in comparison to other cognitive domains such as attention and memory (e.g. Engle, Tuholski, Laughlin, & Conway, 1999). This may reflect, at least in part, the fact that we have little or no first-person insight into our visual abilities. Whilst we are able to reflect on our tendencies to mind-wander or forget, we are unable to reflect on our relative abilities to perceive motion or detect patterns in dots. In theory, it could be the case that normal visual abilities do not vary in the same way as they do for other cognitive domains. In practice, this is not so. Halpern, Andrews, and Purves (1999) reported a twofold difference between highest and lowest performing participants (N = 20) in tests such as wavelength discrimination and contrast sensitivity and a ten-fold difference on an acuity measure. There are twofold differences in the size of vision-related neuroanatomical regions such as primary visual cortex, V1 (Andrews, Halpern, & Purves, 1997; Song, Schwarzkopf, Kanai, & Rees, 2015), and these differences predict susceptibility to certain perceptual illusions (de Haas, Kanai, Jalkanen, & Rees, 2012; Schwarzkopf, Song, & Rees, 2011). As such individual differences in vision are both striking and meaningful, despite our difficulty to imagine seeing the world any differently.

How might individual differences in vision be structured? Here we shall consider three broad possibilities. Firstly, visual ability may be a single monolithic entity analogous to, or equivalent to, general intelligence or 'g' (e.g. Deary, Bell, Bell, Campbell, & Fazal, 2004). Halpern et al. (1999) conducted a Principal Component Analysis over their set of seven tests of visual ability and found a single 'visual performance factor' explained inter-individual variation across almost all of their tasks (accounting for 30% of total variance). This may reflect differences in the total amount of visually dedicated circuitry or it may be due to the major source

* Corresponding author at: School of Psychology, University of Sussex, Falmer, Brighton BN1 9QH, UK.
E-mail address: jamiew@sussex.ac.uk (J. Ward).

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of variation lying within a central hub that contributes to most aspects of vision (e.g. V1 at a cortical level, or photoreceptor density at a more basic level). Earlier research, using a wider range of measures, failed to find support for the notion of a visual 'g' (Guilford, 1967; Thurstone, 1944, 1950). Secondly, visual ability might fractionate according to a small number of anatomical pathways such as dorsal versus ventral stream abilities or magno- versus parvo-cellular abilities. The visual dorsal and ventral stream describes two major cortical pathways arising after V1 that are specialised for colour, object recognition and memory (ventral) versus motion, spatial attention, and vision-for-action (dorsal) (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982). The magno- and parvocellular pathways describe two major sub-cortical pathways: one specialised for motion, low spatial frequency (LSF) and low contrast (magnocellular) and one specialised for colour, high spatial frequency (HSF) and high contrast (parvocellular) (Maunsell, 1987).[1] Evidence for the claim that visual ability is structured according to these divisions has come from, amongst others, visual-evoked potentials in EEG (e.g. Strasburger, Murray, & Remky, 1993) and developmental neuropsychology (Braddick, Atkinson, & Wattam-Bell, 2003). The latter leading to the claim that many (non-ophthalmological) developmental disorder are characterized in terms of 'dorsal stream vulnerability'. However, some recent evidence from normal individual differences in vision failed to support the idea that visual ability fractionates in this way. Goodbourn et al. (2012) used four tests of magnocellular function and found that they tended not to correlate strongly with each other and the correlations were no larger than a test not relying on this system (based on colour). Finally, a third alternative scenario is that there is a multiplicity of visual abilities that are not closely related to each (e.g. Peterzell, Werner, & Kaplan, 1995; Webster & Macleod, 1988). Cappe, Clarke, Mohr, and Herzog (2014) argued for this based on low correlations between performance on different visual tests in their study. This may reflect the quasi-modular functionality of visual cortex or the diversity of retinal and ganglion cell types. The latter was the interpretation favoured by Goodbourn et al. (2012). Of course, these three different explanations are not mutually exclusive as shown in other domains such as intelligence (Deary, 2012; Mackintosh, 2011).

There are several reasons why elucidating the structure of inter-individual differences in vision is important. Wilmer (2008) highlights three reasons that we consider in turn: functional organisation, genetics/environment, and utility. The dominant approach to exploring functional organisation is based on dissociations in performance (e.g. in neuropsychology) or neural specialisation (e.g. in fMRI). A complementary approach is latent variable techniques that isolate psychological mechanisms by identifying a limited number of categories that summarize individual differences in terms of associations of tests or measurements (e.g. as in the study of Halpern et al., 1999). Importantly, these techniques provide the foundation for behavioural genetic studies of individual differences. Methods such as GWAS (genome-wide association studies) are 'phenotype first' approaches that link a known individual difference (e.g. in visual ability) to genetic differences. Finally, an understanding of individual differences may have utility both in terms of predicting real world function (e.g. vision for action; orienting attention; face recognition) and also dysfunction. This includes not only visual disorders but also other developmental or acquired conditions that are not defined by visual disturbances but, for whom, individual differences in vision acts as an endophenotype (perhaps pre-symptomatically). This includes autism spectrum disorder (Simmons et al., 2009) and Parkinson's disease (Uc et al., 2005).

The approach taken in the present study is twofold. Firstly, we administered a diverse set of seven tests of visual perception to a group of ~100 participants and explored the relationship between the tests and measures using a latent variable technique. The tests are summarised in Table 1 and were selected on the basis of their putative weighting towards magno/ventral or parvo/dorsal function (and, hence, is a confirmatory rather than exploratory approach). Secondly, we also ran the identical set of tests on a group of participants with developmental synaesthesia who are hypothesised, based on previous research, to differ in certain visual abilities. Synaesthetes have conscious, reliable visual-like experiences that are evoked by stimuli such as words, letters and numbers (often whether written down, heard in speech, or imagined). Grapheme-colour synaesthetes (GCS) experience colours for letters and numbers. Not only do they have atypical visual-like experiences they also appear to have atypical (non-synaesthetic) visual functioning: they perform better at tests of colour discrimination (Banissy et al., 2013); show increased visual evoked potentials, in EEG, to high-frequency but not low-frequency Gabor gratings (Barnett et al., 2008); have lower phosphene thresholds to occipital lobe stimulation (Terhune, Tai, Cowey, Popescu, & Kadosh, 2011); and have been shown to have worse motion coherence (Banissy et al., 2013). This pattern led to the suggestion that they have enhanced ventral/parvocellular function and normal-to-reduced function of the dorsal/magno stream (Rothen, Meier, & Ward, 2012). However, no previous research has compared a wide range of tests on the same participants and nor have they contrasted distinct forms of synaesthesia. The present study also examines sequence-space synaesthesia (SSS) for whom sequences (e.g. months, numbers) are visualised as spatial configurations (e.g. a twisting line in 3D space). The use of this group enables us to explore whether the differences in perceptual ability are specifically related to the presence of synaesthetic colour in the GCS group. One possibility is that whereas GCS reflects ventral stream ability, SSS reflects differences within the dorsal stream given the dorsal stream specialisation for spatial and numerical cognition (Ramachandran & Hubbard, 2001). We also have a third group of synaesthetes who have both GCS and SSS. This creates a 2×2 between subject design contrasting presence/absence of GCS and presence/absence of SSS (where non-synaesthetic controls have an absence of both).

2. Method

2.1. Participants

The present study recruited a total of 135 participants made up of 101 non-synaesthetes (mean age = 23.7 years; range = 18–63; 31 males) and 34 confirmed synaesthetes (mean age = 30.8 years; range = 18–63; 4 males). A subset of the controls (N = 34) were used as a matched group to the synaesthetes (mean age = 30.1 years; range = 18–63; 11 males). All participants had normal or corrected-to-normal vision and did not self-report colour-blindness.

The presence of grapheme-colour synaesthesia was confirmed using an online test of colour test-retest consistency (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). This approach is extensively used but obviously presupposes that the associations are consistent (Simner, 2012). Grapheme-colour synaesthetes had an average consistency score of 0.78 (range = 0.46–1.47) where the score of 1.43 provides optimal diagnostic sensitivity and specificity

[1] It has been suggested that there is a direct relationship between these cortical and sub-cortical systems (such that parvocellular system is more important for ventral stream, and magnocellular for dorsal stream) although this division is not absolute and parvo- and magno- systems feed into both dorsal and ventral streams to at least some degree (Merigan & Maunsell, 1993).

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