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An exploratory factor analysis of visual performance in a large population

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ABSTRACT

A factor analysis was performed on 25 visual and auditory performance measures from 1060 participants. The results revealed evidence both for a factor relating to general perceptual performance, and for eight independent factors that relate to particular perceptual skills. In an unrotated PCA, the general factor for perceptual performance accounted for 19.9% of the total variance in the 25 performance measures. Following varimax rotation, 8 consistent factors were identified, which appear to relate to (1) sensitivity to medium and high spatial frequencies, (2) auditory perceptual ability (3) oculomotor speed, (4) oculomotor control, (5) contrast sensitivity at low spatial frequencies, (6) stereo acuity, (7) letter recognition, and (8) flicker sensitivity. The results of a hierarchical cluster analysis were consistent with our rotated factor solution. We also report correlations between the eight performance factors and other (non-performance) measures of perception, demographic and anatomical measures, and questionnaire items probing other psychological variables.

1. Introduction

Different individuals perceive the world differently from one another. These differences may arise from inherited variations in the structure of the visual and auditory systems or from variations in experience during an individual's lifetime. Variations in human perception have been perhaps less studied than variations in cognitive skills. However, not only do they have significant impact on our behaviour but they also offer a powerful method of analysing perceptual mechanisms (Kanai & Rees, 2011; König & Dieterici, 1892; Peterzell, 2016; Wilmer, 2008).

Whenever visual or auditory performance is measured in a sample of participants, there is variance evident in the data. This variance comes from three sources: (i) instrumental and other measurement error, (ii) within-individual variation (e.g. temporal fluctuations in motivation and arousal), and (iii) between-individual variation, i.e. persisting differences between participants caused by between-individual variation in processes underlying perceptual functions. To demonstrate true between-individual differences it is necessary to show one or both of two types of result. First, one may show a significant test–retest reliability for the trait of interest (Spearman, 1904b; Wilmer, 2008). Second, one can demonstrate a significant correlation between the trait of interest and another, independent, phenotypic or genotypic measure (Kanai & Rees, 2011; Wilmer, 2008).

Correlational methods can be successfully used to analyse the mechanisms that underlie traits of interest. A classical example in vision was the identification of the genetic polymorphisms that underlie colour vision deficiency and that also contribute to the normal variation in Rayleigh matches (Nathans, Piantanida, Eddy, Shows, & Hogness, 1986; Winderickx et al., 1992). More recently, genome-wide association has been applied to variation in visual performance in the PERGENIC cohort, whose data are the basis of the present paper: Correlations have been found between genetic polymorphisms and hetereochromatic flicker photometric settings (Lawrance-Owen et al., 2014), phorias (Bosten et al., 2014), face detection (Verhallen et al., 2014) and sensitivity to 'frequency-doubled' gratings (Goodbourn et al., 2014). In another fruitful use of the correlational method, relationships have been discovered

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between the size of cortical structures and visual performance on a range of tasks, including visual acuity (Duncan & Boynton, 2003), orientation sensitivity (Song, Schwarzkopf, & Rees, 2013), susceptibility to geometric illusions (Schwarzkopf, Song, & Rees, 2011) and rate of perceptual rivalry (Kanai, Bahrami, & Rees, 2010).

A celebrated approach to the analysis of correlations is factor analysis (Mulaik, 2009; Spearman, 1904a, 1927; Thurstone, 1931). Factor analysis aims to discover whether a smaller set of underlying unobserved variables – known as *factors* – are responsible for the intercorrelations between a set of observed variables. The meanings of any factors revealed by factor analysis are open to interpretation, but in psychology they have often been thought to relate to the psychological processes that determine the variation in the observed data.

Factor analysis has been comprehensively applied in the field of cognition, to address the question of whether cognitive ability is determined by a set of independent factors or whether it is determined by a single underlying factor, Spearman's *g* (Mackintosh, 2011; Spearman, 1904a; Thurstone, 1944). For vision, an equivalent question is whether the observed variation in performance on a battery of visual tasks is determined for each task separately, or whether it is determined by a single underlying factor or small set of factors,

Several studies have applied factor analysis to perception. An early example was the analysis of 22 auditory tests by Karlin (1942). Particularly celebrated is the study of Thurstone (1944), who administered 40 tests to 194 subjects. Most of the tests were visual, including some measures of "low-level" visual processes such as dark adaptation, peripheral span and flicker fusion, and many tests of "high-level" processes such as Necker cube rivalry, various geometric illusions, Gestalt figure completion, colour-form memory, block design and the Gottschaldt figures. Also included were some non-visual tests, including reaction time to an auditory tone, social judgement and a test of social influence. Thurstone cautioned that his study was exploratory and required confirmation by future studies, but he found 11 factors, the first seven of which he interpreted as perceptual closure, susceptibility to geometric illusions, reaction time, perceptual alternation, ability to manipulate two alternative mental processes, perceptual speed and general intelligence.

Since Thurstone's study, researchers have applied factor analysis to a range of visual tasks, but they generally have been concerned with particular aspects of visual perception. A good example is provided by Peterzell and Teller's (Dobkins, Gunther, & Peterzell, 2000; Peterzell & Teller, 1996; Peterzell & Teller, 2000; Peterzell, 2016) studies of spatial, temporal and chromatic contrast sensitivity, which have supported the idea that sets of distinct visual factors underlie contrast sensitivity functions. In the domain of colour, factor analysis has been used to investigate sensitivity as a function of wavelength (Jones, 1948; Jones & Jones, 1950), to test the independence of the cardinal colour mechanisms (Gunther & Dobkins, 2003), to explore the sources of individual variation in colour matching (MacLeod & Webster, 1983), to investigate wavelength discrimination (Diener, 1986; Pickford, 1962), and to explore sources of variation in tests for colour vision deficiency (Aspinall, 1974). Other authors have examined measures of perceptual closure (Beard, 1965; Keehn, 1956; Mooney, 1954; Thurstone, 1950; Wasserstein, Barr, Zappulla, & Rock, 2004).

A smaller number of studies have followed Thurstone (Thurstone, 1944, 1950) in using factor analysis (or the related method of principal components analysis; PCA) to study the factors underlying variation in a large range of visual abilities. For a group of 20 participants, Halpern, Andrews, and Purves (1999) made measurements of orientation discrimination, wavelength discrimination, contrast sensitivity, vernier acuity, motion direction discrimination, velocity discrimination and identification of complex forms. They observed many significant intercorrelations between the tests, and concluded, using PCA, that a single factor (accounting for 30% of the total variance) predicts a portion of the variance on each test apart from discrimination of motion direction.

For a group of 40 participants, Cappe, Clarke, Mohr, and Herzog (2014) applied PCA to measurements of visual acuity, vernier acuity, backward masking, contrast sensitivity and bisection discrimination. They emphasised the low correlations between pairs of tasks, with only four significant correlations, for which shared variance ranged between 10% and 30% (Test-retest reliabilities for individual tasks were not reported, however). Using PCA, they found that one factor explained 34% of the total variance. However, they applied a different criterion to that of Halpern et al. (1999) in deciding how much variance a common factor must explain, concluding that 34% shared variance was *not* evidence for a single factor underlying the intercorrelations between visual tests.

In a study of 101 normal participants, Ward, Rothen, Chang, and Kanai (2016) obtained data for seven visual tasks: detection of gabors, contrast sensitivity, detection of Glass patterns, detection of coherent motion, visual search, detection of curvature and judgement of temporal order. They applied a factor analysis to test the hypothesis that there are two visual factors that reflect the activity of the parvocellular and magnocellular systems. They found two components, which accounted for 19% and 18% of the total variance. Tasks involving high spatial frequencies generally loaded on the first component, and tasks involving low spatial frequencies on the second. The authors concluded that this was compatible with a magnocellular–parvocellular distinction.

The present study continues the tradition of Thurstone (1944) and those who have followed, in applying factor analysis to a range of visual tasks to explore the underlying causes of individual variation in visual ability. We do this on a much larger sample ($n = 1060$) than has been used previously, and we include 25 visual, oculomotor and auditory measures. Our primary analysis is an exploratory factor analysis; and we demonstrate the reliability of the analysis by showing that very similar factors emerge if the total cohort is randomly divided into two subsets of participants. We also show that a comparable structure is recovered when the data are entered into a hierarchical cluster analysis. In a further analysis, we correlate factor scores with additional measures gathered from questionnaires (e.g. personality and Autism-spectrum Quotient), with subjective (non-performance) measures of visual function, and with demographic and anatomical measures (e.g. sex, iris colour and digit ratio).

2. Methods

2.1. Participants

1060 participants (647 female) took part in the PERGENIC study (e.g. Goodbourn et al., 2012; Lawrance-Owen et al., 2013). Their ages ranged from 16–40 (mean 22.1; s.d. 4.1). They were recruited from the Cambridge area, and many were students at the University of Cambridge. Participants were paid £25 for taking part. A subset of 105 participants were selected at random to return for a second testing session on a different day, an average of 26.4 days (s.d. 23.3 days) after their first, allowing us to measure test–retest reliabilities. All participants in our sample were of self-reported European origin.

The study was approved by the Cambridge Psychology Research Ethics Committee and was carried out in accordance with the tenets of the Declaration of Helsinki. All participants gave written informed consent before taking part.

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