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Individual differences in human eye movements: An oculomotor signature?

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ABSTRACT

Human eye movements are stereotyped and repeatable, but how specific to a normal individual are the quantitative properties of his or her eye movements? We recorded saccades, anti-saccades and smooth-pursuit eye movements in a sample of over 1000 healthy young adults. A randomly selected subsample (10%) of participants were re-tested on a second occasion after a median interval of 18.8 days, allowing us to estimate reliabilities. Each of several derived measures, including latencies, accuracies, velocities, and left-right asymmetries, proved to be very reliable. We give normative means and distributions for each measure and describe the pattern of correlations amongst them. We identify several measures that exhibit significant sex differences. The profile of our oculomotor measures for an individual constitutes a personal oculomotor signature that distinguishes that individual from most other members of the sample of 1000.

1. Introduction

Eye movements are the most common of all human actions: every second of our waking life we make approximately three of the rapid, stereotyped movements that are saccades (Carpenter, 2004). It is known, however, that there are reliable individual differences in the characteristics of both saccades and smooth-pursuit eye movements (Ettinger et al., 2003; Katsanis, Taylor, Iacono, & Hammer, 2000; Klein & Fischer, 2005; Meyhofer, Bertsch, Esser, & Ettinger, 2016; Smyrnis, 2008; Vikesdal & Langaas, 2016; Wostmann et al., 2013); and it has sometimes been suggested that oculomotor measures are specific enough to be used for biometric identification (e.g. Kasprowski & Ober, 2004; Komogortsev, Karpov, & Holland, 2016; Komogortsev, Karpov, Price, & Aragon, 2012; Poynter, Barber, Inman, & Wiggins, 2013; Zhang, Laurikkala, & Juhola, 2015). We have obtained a comprehensive set of oculomotor measures for over 1000 healthy young adults and have established the reliabilities of the measures by re-testing 10% of the participants after a median interval of 18.8 days. Each measure in itself proves highly reliable; and the *profile* of these parameters does constitute a motor signature that distinguishes an individual from most other members of the cohort.

We included in our battery three types of oculomotor task. In the pro-saccade task, the observer fixates centrally, a peripheral visual target appears suddenly, and he or she is required to fixate the target as quickly as possible (Leigh & Kennard, 2004). In the anti-saccade task, the participant is required to fixate in the exact

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opposite direction from that of the target (Evdokimidis et al., 2002; Hallett, 1978). In the smooth-pursuit task the participant is asked to maintain fixation on a moving visual target.

Abnormalities of these three tasks have been reported in many psychiatric and neurological pathologies (Klein & Ettinger, 2008; Leigh & Zee, 2015) and have sometimes been proposed as endophenotypes (Gottesman & Gould, 2003); this is a further reason to know the range of variation of oculomotor measures in the normal population and their test-retest reliabilities. In the anti-saccade task, for example, schizophrenic patients make more direction errors, i.e. make more erroneous pro-saccades, than do controls (e.g. Fukushima et al., 1988) and their anti-saccades have longer latencies (Fukushima, Fukushima, Morita, & Yamashita, 1990); for a review, see Hutton and Ettinger (2006). In ocular tracking ('smooth pursuit') tasks, schizophrenics show an increased number of intrusive saccades and a reduced pursuit gain – defined as the ratio of eye velocity to target velocity (see e.g. Damilou, Apostolakis, Thrapsanioti, Theleritis, & Smyrnis, 2016; Diefendorf & Dodge, 1908; Leigh & Zee, 2015; Levy, Holzman, Matthysse, & Mendell, 1993; O'Driscoll & Callahan, 2008). The latencies of pro-saccades, and the distributions of latencies, are also known to be abnormal in, for example, Parkinson's disease (Perneczky et al., 2011) and in Huntington's disease (Lasker & Zee, 1997).

In the case of normal subjects, only a few studies have examined how variation in one eye-movement task relates to that in another. To what extent do different measures depend on a single underlying mechanism or are the several oculomotor measures completely independent? To address such questions, one can examine the correlations between various eye-movement measures for a large number of individuals: both the absence and the presence of correlations will then give insights into the underlying mechanisms (see Wilmer (2008) for a recent review). Typically, a latent variable analysis (Loehlin, 2004), such as factor analysis, is used to examine the relationship between different variables. One study that has analysed eye movements in this way was that by Fischer, Biscaldi, and Gezeck (1997), who applied factor analysis to six measures derived from pro- and anti-saccade tasks: they found two factors, one relating to anti-saccade performance and one relating to pro-saccade performance. We here extend such an analysis to a wider range of eye-movement measures.

To allow comparisons between eye-movement studies and to disentangle whether the variation between studies arises from the different populations studied or from the idiosyncratic tasks used, it is desirable to standardise the tasks. Smyrnis (2008), in a comprehensive review of the methodology of saccadic and smooth-pursuit paradigms, sets out recommendations for experimental design, target parameters, sampling frequency and data analysis. The present study has been guided by these recommendations. For a group of over 1000 adults, we report the range, distribution and reliability of a large number of oculomotor measures. Correlations were carried out to establish the relationship between each pair of measures. We used factor analysis to investigate whether the observed covariation could be explained by a smaller number of hypothetical factors. We also report correlations with sex and with personality measures. Finally, we examine the extent these standard eye-movement measures constitute a unique signature for a particular individual.

2. Methods

2.1. Participants

There were 1058 participants (413 male and 645 female; age range 16–40, mean = 22.14, SD = 4.09). They were recruited to take part in the PERGENIC test battery, which consisted of a number of optometric, perceptual and oculomotor tests (Goodbourn et al., 2012). All participants were of European ancestry. A large proportion were students from Cambridge University.

In order to establish the test–retest reliability of our measures, a randomly selected 10% of the sample (105 participants; 42 male and 63 female; age range 16–39, mean = 21.66, SD = 4.01) completed the PERGENIC test battery twice. In all but three cases, the two testing sessions were at least one week apart: the range was 2–105 days, with a mean of 26.4 days and a standard deviation of 23.3 days. The median was 18.8 days.

The oculomotor tests occupied approximately 25 min of the total 2.5-h testing duration. Before completing the psychophysical and oculomotor tests, participants underwent an optometric assessment.

The study received approval from the Cambridge Psychology Research Ethics Committee and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants gave written consent after having been given information about the experiment. They were paid a fee of £25 for their participation.

2.2. Apparatus

Stimuli were presented in a darkened room on a Sony GDM-F520 CRT monitor using a Cambridge Research Systems VSG 2/5 graphics card. The refresh rate of the monitor was 100 Hz. The target for each task was a white disk with a diameter of 0.3° of visual angle presented on a grey background; the target and background had luminances of 75 cd/m^2 and 25 cd/m^2 respectively. The background was continuously present during inter-stimulus intervals. A chin-rest was used to minimise head movements and maintain a viewing distance of 60 cm.

Eye movements were recorded using the head-mounted JAZZ-novo multisensory system (Ober Consulting, Poznan, Poland). The JAZZ-novo measures horizontal and vertical eye rotations using infrared oculography. It is also equipped with two uni-axial gyroscopes that measure the velocity of horizontal and vertical head rotations. All signals are sampled at 1 kHz. The measurable ranges for horizontal and vertical eye rotations are ±35° and ±25°, respectively. The noise level (along the horizontal axis) is equivalent to 6 min of visual angle. Each measurement of eye rotation is an average of the two eyes; this cycloptic measure is intrinsic to the JAZZ-novo sensor system. The signals from the JAZZ-novo were synchronised with the CRT by means of the Windows-independent timer present on the Cambridge Research Systems VSG 2/5 graphics card. The synchronization was accurate to 1 ms (tested empirically).

2.3. Analysis of oculomotor data

All oculomotor data were processed and analysed using purpose-built programs written in MATLAB (MathWorks, UK). The raw output from the JAZZ-novo system is a digital 12-bit signal. The JAZZ-novo has an in-built mechanism to centre the signal if it approaches the limit of the 12-bit range (0–4096); correction was made for this effect before data processing.

Nine calibrations were performed in the course of testing each participant (see below, §2.4). The gain and the offset for each calibration were calculated using linear regression of the eye signal against the target amplitudes. These factors were applied to the eye-movement data following the calibration. On rare occasions, a particular calibration did not yield an adequate calibration factor (as assessed with goodness of fit statistics) and the closest calibration in time (of the nine) was used in its place.

The eye-movement signal was processed following Bahill, Kallman, and Lieberman (1982). The raw amplitude signal (horizontal and vertical) was filtered with a 300 Hz low-pass filter. A

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