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SENSORY NERVE CONDUCTION AND INTELLIGENCE: A REPLICATION

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Summary—A replication was undertaken of our previous work relating the conduction parameters of variability and velocity of the electrically stimulated peripheral median nerve to psychometric test IQ and EPQR Psychoticism. Once again, we failed to find any significant correlation between measures of nerve conduction velocity and IQ. Further, we failed to replicate a previous correlation of 0.37 between EPQ Psychoticism and conduction velocity. However, we did partially replicate the correlation between conduction variability and IQ, although the statistical significance of this correlation depended upon a correction for an excessive restriction of range in IQ and on the notion of an order effect in the testing procedures. Finally, it was demonstrated that the measurement of nerve conduction velocity via just-above-threshold stimulus levels yielded measurement reliability and parameter stability equal to that found using supramaximal stimulation.

INTRODUCTION

Human peripheral nerve transmission characteristics have recently become the focus of attention to researchers interested in the biological foundations of intelligence. Two parameters have been examined in some detail, nerve conduction velocity (the speed at which a nerve impulse travels through axons and across synapses), and nerve conduction variability (the variability in action potential response to a constant stimulus). Vernon (1990) briefly reviewed some early work in this area, confined solely to patellar reflex arc responses and achilles tendon reflex (Rounds, 1928; Travis, 1928; Travis & Hunter, 1928; Travis & Young, 1930). The results from these early studies were conflicting and subsequently of little interest to the psychological world at that time. However, in the last few years, work in three laboratories has indicated that peripheral nerve transmission characteristics may be related to psychometric intelligence test scores. Reed (1984), in a discussion of the physiological mechanisms associated with the heritability of intelligence, first suggested that a correlation may exist between peripheral and brain nerve conduction velocity. This suggestion was prompted in part by the work of Hegmann (1972, 1975, 1979) and Reed (1983) on the genetics of nerve conduction velocities in mice.

The first reported work assessing the relationship between human peripheral nerve conduction characteristics and intelligence was that carried out by Vernon and Mori, reported initially at a conference (Vernon & Mori, 1989), and subsequently reported in full in Vernon and Mori (1992). Using data from 85 mixed sex university students, they computed three measures of conduction velocity from the right arm median nerve in the finger–wrist–arm segment. Electrical stimulation of the nerve was supramaximal. A first principal component was computed for the 10 subtests of the Multidimensional Aptitude Battery (Jackson, 1984) and separately for the three nerve conduction velocity estimates. Correlating *S*s' scores on each principal component yielded a correlation of 0.42, indicating higher conduction velocity in higher IQ *S*s. In addition, it was found that the wrist-to-finger conduction velocities correlated higher with IQ and reaction time than the velocities computed from the wrist-to-elbow or wrist-to-axilla. Test–retest coefficients based upon 15 of the *S*s, over a period from 1 to 3 weeks, indicated high reliability of measurement: 0.86 (wrist-to-finger), 0.81 (wrist-to-elbow), and 0.95 (wrist-to-axilla).

Vernon and Mori (1992) reported a replication of their initial experiment using a further 88 mixed sex undergraduate students, following the same measurement procedures. Conduction

velocity was computed only between the finger–wrist segment of the median nerve. Once again, a first principal component composite IQ measure was used for correlational purposes. The correlation between conduction velocity and IQ was 0.48.

Barrett, Daum and Eysenck (1990), in a study using 44 mixed sex *S*s, examined the relationships between several measures of median nerve transmission characteristics, psychometric intelligence (Ravens Advanced Progressive Matrices, Raven, 1983b), personality [using the Eysenck Personality Questionnaire (EPQ), Eysenck & Eysenck, 1975], and 3-bit choice reaction time. Both conduction velocities and action potential variabilities were computed from a segment of nerve between the finger and wrist, on both arms. No significant correlation was found between nerve conduction velocity and intelligence or choice reaction time, rather, it was variability in conduction that correlated −0.44 with IQ. However, a statistically significant correlation of 0.37 between velocity and EPQ Psychoticism was observed. Electrical stimulation of the nerve was between threshold and 2 mA above threshold; effectively 15–20 mA below supramaximal levels.

Reed and Jensen (1991) reported a study carried out on 200 male college and university students, assessing nerve conduction velocity of the median nerve in the wrist–elbow segment of a *S*'s preferred hand. The velocities were correlated with scores on Ravens Standard (Raven, 1983a) and Advanced Progressive Matrices, and with 3 reaction time tasks (simple, 3-bit, and oddman). Electrical stimulation of the nerve was supramaximal. Arm conduction velocities showed no relationship with IQ and inconsistent relationship to the various measures of reaction time. Test–retest reliability of the conduction velocities was computed using 14 *S*s who were re-assessed from several days to several weeks after their initial test session. This computed reliability was 0.63. In addition to the wrist–elbow conduction velocities, Reed and Jensen computed an estimate of retina to visual cortex brain pathway nerve conduction velocities, computed by measuring latencies of components from visual averaged evoked potentials. This brain conduction velocity correlated 0.26 with IQ. This particular result is reported in detail in Reed and Jensen (1992).

It would appear from the above studies that only Vernon and Mori have been able to demonstrate a consistent and significant peripheral nerve conduction velocity and IQ relationship. Although Reed and Jensen's work did indicate a brain pathway velocity relationship, this was based upon inferred nerve pathway lengths based upon head length measurements (although it is reasonable to assume that these pathway lengths might be proportionate estimates to the true nerve pathway length). It is, therefore, important that we replicate our own work in this area. The major difference between our work and that of Reed and Jensen and Vernon and Mori is in the level of electrical stimulation applied to the nerve tissues. We have used stimulation that is only 2 mA above threshold, the other investigators all used supramaximal stimulation (usually about 15–20 mA above threshold). Both Reed and Jensen and Vernon and Mori suggest that as supramaximal stimulation is guaranteed to enervate the fastest fibres within the median nerve bundle, only this level of stimulation will produce reliable conduction velocity measurement. Submaximal stimulation is assumed to enervate mainly lower speed fibres in an inconsistent manner (some fast fibres may fire also), leading to unreliable, unstable, measures of conduction velocity that are unlikely to correlate with any other measurement variable, including IQ.

Thus, in the experiment reported below, an attempt is made to replicate our earlier work and focus directly on the issue of the measurement reliability of conduction velocity and variability parameter estimates. The parameters estimated are confined solely to those previously shown to be significantly related to psychometric variables. This includes conduction velocity and variability. With regard to differences in methodology, we have chosen to use the 2 mA above threshold stimulus only. This condition yielded the clearest results and also the best defined action potentials. In order to attempt to increase the test–retest reliability of the variability estimates, we have used 64 epochs (rather than just the 20 in our first study) to compose the averaged nerve action potential. Finally, with regard to the electrode montage, we increased the earth electrode spread, used a single reference electrode, and acquired data from only 3 instead of 4 recording electrodes. We also closed the gap slightly between recording electrodes, from about 25 to 16 mm. These measures were taken in order to reduce shock transients and hopefully to improve the quality of acquired data, especially on recording electrode 3, the one furthest from the wrist area.

METHOD

Subjects

Sixteen male and 44 female volunteers took part in the experiment. They were recruited from the general public via advertisements placed within local newspapers. The age range of the male *S*s was from 16 to 37 years, with a mean of 26.63 and standard deviation (SD) of 7.26. The age range of the female *S*s was from 18 to 53 years, with a mean of 34.53 and SD of 8.87. All volunteers were established as having no known previous medical history concerning peripheral nerve function trauma or chronic degradation of sensory functioning. Each *S* was paid £10.00 for their participation in the experiment.

Psychometric tests

*S*s were administered the EPQ-Revised (EPQR; Eysenck, Eysenck & Barrett, 1985) questionnaire, assessing the four personality dimensions of Psychoticism, Extraversion, Neuroticism, and Social Desirability. In addition, the I_7 personality questionnaire (Eysenck, Pearson, Easting & Allsopp, 1985) was also administered, assessing a further three personality dimensions of Impulsivity, Venturesomeness, and Empathy. Intelligence was assessed using the Jackson (1984) Multidimensional Aptitude Battery (MAB), a group administerable analogue of the Wechsler Adult Intelligence Scale—Revised. The MAB yields three global IQ measures, Performance, Verbal, and Full-Scale.

Action potential acquisition hardware

Using both hands, adminstration order being counterbalanced across *S*s, orthodromic electrical stimulation of the median nerve was accomplished with a MEDELEC ST10 stimulator, providing positive, 0.1 msec duration, constant current electrical pulse stimulation using two ring electrodes placed on a *S*'s middle finger. Current stimulation was available in 1 mA steps. Skin surface temperature was measured over four areas along the hand and wrist using bead thermistor probes, accurate to $\pm 0.1^{\circ}$C. The four probes were scanned 10 times a second by a COMARK COMPUFACE utility I/O interface unit. This unit was under the control of a MASSCOMP M6600 computer. The MASSCOMP also controlled a PHILLIPS type KL 7500 150 watt infrared heat lamp via a solid state relay that switched the lamp on and off at the nearest zero crossing of the mains 50 Hz supply. Analogue data from *three* recording electrodes were acquired by the MASSCOMP computer, using simultaneous sample and hold-burst mode sampling. Acquisition sampling speed was 100 kHz per channel. Signal amplification was effected using a BIODATA PA400 4 channel amplifier and pre-amp unit.

Electrodes and electrode montage

Recording electrodes were standard EEG Ag–AgCl 9 mm disc electrodes. The stimulating ring electrodes were stainless steel wire loops, issued as standard with the ST10 stimulator. The stimulating electrodes were placed on the distal phalanx (anode) and interphalangeal joint (cathode) of the third finger. Figures 1 and 2 below provide a schematic view of the electrode montage.

Electrodes 1–3 were referenced against a single electrode placed on the outside edge of the wrist, in line with electrode No. 2 (monopolar recording). The linked earth electrodes were placed on the back of the hand, as shown in Fig. 2. One electrode was positioned over the 3rd finger intertendinous connection, the other over the first dorsal interosseus muscle, near the trapezoid bone. Vernier gauges and calipers were used to place the recording electrodes equidistant and at the midpoint of the wrist in a straight line. All measurements between stimulating and recording electrodes were made from the midpoints of each electrode, using vernier calipers. Recording electrodes were placed approx. 16 mm apart.

The recording, reference, and earth electrodes were affixed using collodion (after skin preparation with surgical spirit). NaCl electrode gel was applied to each electrode. *All* electrode impedances were reduced to less than 5 kΩ where possible, using a blunt needle for skin abrasion. The maximum permitted impedance was 10 kΩ. The stimulating electrodes were applied to the third finger phalanxes, the areas having been prepared using surgical spirit. A small amount of electrode gel

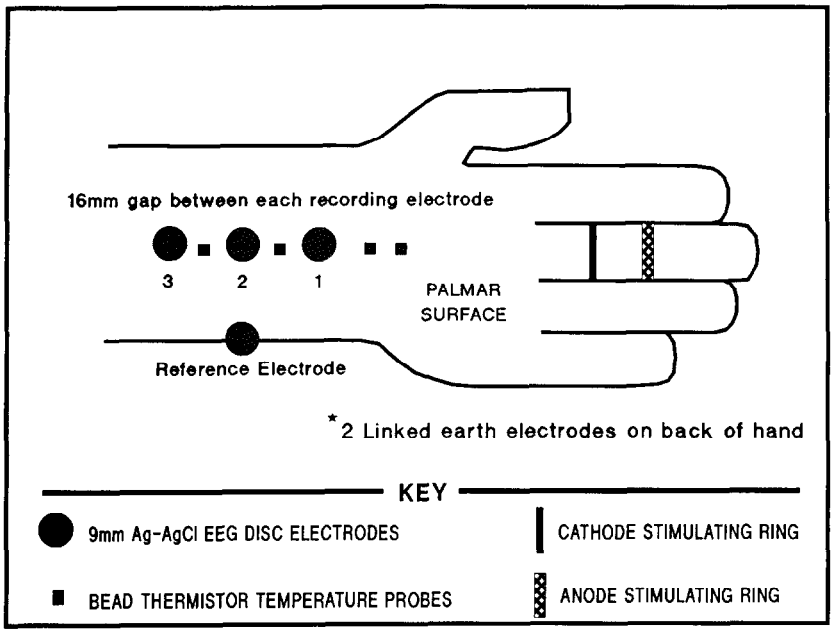

Fig. 1. Electrode montage.

was applied to the dorsal surface of both ring electrodes. The *S* was then connected into the appropriate hardware, with the wrist and arm resting upon the arm of a chair in which he/she was seated. The *S*'s hand was extended palmar surface up. Analogue 3rd order butterworth filters in the amplifier were set at 79.58 Hz (3 dB loss) high pass and 1 kHz (3 dB loss) low pass for each recording electrode channel. Finally, the infrared heat lamp was then extended immediately above the *S*'s palm and wrist at a height of about 15″.

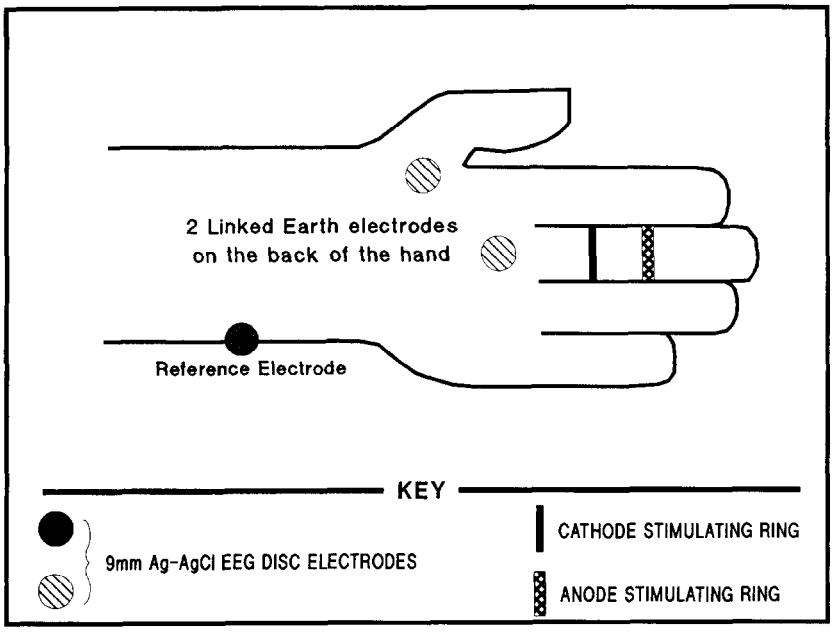

Fig. 2. Earth electrode positions.

Action potential acquisition procedure

Prior to data acquisition, the 3 input amplification channels were calibrated using a synthesized sine-wave signal source, as detailed in Barrett *et al.* (1990). In order to locate the sensory threshold of the median nerve, the tester used a utility program which triggered a stimulus on the ST10 and plotted the resultant nerve activity acquired from all three recording electrodes on-screen. By varying the current delivered by the ST10, starting at 1 mA and incrementing in 1 mA steps, visual confirmation of the compound sensory nerve action potential (SNAP) could be easily obtained. The current value at which the SNAP was visually identified and confirmed was used as that *S*'s threshold value. All experiment trial stimuli were subsequently delivered at 2 mA above threshold, equivalent to Condition 4 trials in Barrett *et al.* (1990).

The trial sequence

For each *S*, 64 shock stimuli were administered, with at least a 2 sec interstimulus interval. The MASSCOMP would begin by sampling the four temperature channels, if the mean of these temperatures was $<34°C$ then the heat lamp would be turned on. If the mean temperature was $>34°C$ then the lamp would be turned off. Until the temperature mean was exactly equal to 34°C, this temperature sampling and calculation would take place 10 times a second. When 34°C was achieved, the MASSCOMP would turn the lamp off (if on), trigger the ST10 to deliver a stimulus, and acquire data from the 3 channels at 100 kHz for 10 msec, yielding 1000 sample points per channel. The four channel data were displayed almost instantaneously on the tester's experiment control console, as were other ongoing control parameters. Data were always acquired with the heat lamp switched off.

Parameter computation

For both hands, and for each of the 3 recording electrodes, the 64 (or less) trials were arithmetically averaged to provide an averaged sensory nerve action potential (ASNAP). Prior to averaging, each SNAP trace was mean detrended (subtracting the mean amplitude of the trace from each sample point) and amplitude artifacted (excluding those SNAPs where at least one post-stimulus artifact sample point fell outside the range $\pm 50\mu V$). For each ASNAP, 2 parameters were computed:

1. *Variability*: variability of the ASNAP was computed using the sum of the individual variances for each time point computed across the 64 (or less) trials. This sum was divided by the number of variances in order to provide the mean variability estimate. A computation window between 2 and 9 msec was used, corresponding to the *unrestricted* window as used in Barrett *et al.* (1990).

$$\text{Variability} = \frac{\sum_{i=1}^{N}\left[\frac{\sum_{j=1}^{K}(X_j - \bar{X}_i)^2}{K}\right]}{N}$$

where: N = the number of sample points i, over which to compute the calculation; K = the number of epochs over which the sum is computed: and X = the array of values for one sample point i, across epochs j.

2. *Velocity*: estimates of velocity were computed from two sources. Firstly, using the distances between electrodes 1, 2, and 3 (between 1 and 2, 1 and 3, 2 and 3) and secondly, using the distances measured from the stimulating cathode electrode to electrodes 1, 2, and 3. Velocities were expressed in units of metres per second (mps) from the shock onset to the ASNAP negative peak. Although the ASNAP potentials are triphasic, the first and 3rd phase positive peaks were not clearly defined in over half the *S*s tested, therefore we adopted the middle negative peak as the estimator of conductance latency (peak latency). Although Podivinsky (1967) has expressed preference for the initial phase latency (onset latency) to be used in velocity studies, both Ma and Liveson (1983), and Oh (1984) recommend use of the peak latency where ASNAP onset is ill-defined.

Table 1. Descriptive statistics of the physiological and psychometric variables

Variable	*N*	Mean	SD	Minimum	Maximum
MAB Performance IQ	60	108.80	11.87	81.00	135.00
MAB Verbal IQ	60	112.48	11.54	86.00	135.00
MAB Full-Scale IQ	60	111.02	11.06	90.00	136.00
EPQR—Psychoticism	60	6.47	4.67	0.00	18.00
EPQR—Extraversion	60	14.30	5.27	2.00	22.00
EPQR—Neuroticism	60	14.17	4.97	3.00	22.00
EPQR—Social Desirability	60	6.18	3.86	0.00	16.00
I_7—Impulsivity	60	8.13	4.47	0.00	18.00
I_7—Venturesomeness	60	8.00	4.31	0.00	15.00
I_7—Empathy	60	13.68	3.39	3.00	19.00
Velocity—electrode 1, occasion 1	59	39.76	3.54	29.35	47.33
Velocity—electrode 1, occasion 2	58	39.97	3.11	30.94	46.26
Velocity—electrode 2, occasion 1	55	40.94	6.34	24.34	60.35
Velocity—electrode 2, occasion 2	59	40.95	6.03	21.66	57.76
Variability—electrode 1, occasion 1	58	8.95	7.71	1.57	33.89
Variability—electrode 1, occasion 2	57	10.78	9.75	1.20	39.60
Variability—electrode 2, occasion 1	59	5.89	6.01	1.50	40.37
Variability—electrode 2, occasion 2	59	6.64	5.23	1.25	31.26

RESULTS

From the initial parameter computation analyses and from visual inspection of the ASNAPs, it was apparent that electrode 3 data was of very poor quality. This is the electrode furthest away from the stimulation area. As in study 1, the ASNAP peaks and troughs were less well defined and thus caused much ambiguity in the location of the peak latency. Therefore, electrode 3 parameter values were dropped from all further analyses. Table 1 presents the means, standard deviations (SD), and minimum and maximum values for the variables used in the correlational analyses. As can be seen from this table, some data was lost from 1 or 2 *S*s due to the amplitude artifact analysis and where the computed velocity or variability parameters were >5 SD from the mean of the parameter distribution.

Also apparent from this table is that the IQ distribution is biased slightly toward above average ability. The expected SD for the MAB IQ is 15, the value for the 60 *S*s in this study is 11.06. In fact, polarizing the IQ distribution yields only 9 *S*s with IQs between 90 and 100, and 14 *S*s with IQs between 120 and 136. In comparison with previous results, the velocity and variability parameters are very close to the values reported in Barrett *et al.* (1990).

Table 2 presents the correlations between the MAB composite IQ scores and the 2 electrode channel nerve conduction parameters.

As can be seen from this table, we find no relationship between nerve conduction velocity and IQ. The variability correlations, are significant at $P < 0.05$ one-tail although only on the second occasion for both Verbal and Full-scale IQ. This result is unlike that of Barrett *et al.*'s (1990) results where both occasion parameters correlated significantly with Raven IQ. However, our previous study had also hinted at an order effect running through the data, with second occasion parameters tending to correlate higher with psychometric IQ than the first occasion parameters. In both studies, the order of hand tested was counterbalanced across *S*s, thus no simple explanation based upon right or left hand bias is possible. It may have more to do with the actual testing procedures themselves than any other factor. More will be said about this in the discussion.

In order to examine the test–retest reliability of the parameters, we correlated the parameter values from occasion 1 with those computed on occasion 2. Essentially, this is a reliability parameter that assesses measurement stability over a very short intervening period and tests directly

Table 2. Correlations between nerve conduction parameters and IQ scores

	Verbal IQ	Performance IQ	Full-scale IQ
Velocity—electrode 1, occasion 1	0.04	−0.01	0.03
Velocity—electrode 1, occasion 2	0.08	−0.01	0.05
Velocity—electrode 2, occasion 1	0.11	0.09	0.11
Velocity—electrode 2, occasion 2	−0.11	−0.14	−0.13
Variability—electrode 1, occasion 1	−0.04	−0.06	−0.04
Variability—electrode 1, occasion 2	−0.25	−0.17	−0.23
Variability—electrode 2, occasion 1	−0.08	−0.08	−0.08
Variability—electrode 2, occasion 2	−0.26	−0.21	−0.26

Table 3. Test–retest reliability of the conduction velocity and variability parameters

	Uncorrected	Outliers removed
Velocity—electrode 1	0.82 (58)	0.81 (51)
Velocity—electrode 2	0.32 (54)	0.85 (42)
Variability—electrode 1	0.34 (56)	—
Variability—electrode 2	0.01 (58)	—

The figures in parentheses are the number of observations over which the correlations were computed.

for the repeatability of measurement using two completely different sets of electrodes and placements. If our electrode placement measurement procedures and recording techniques are accurate and objective, then we should see a high reliability of measurement between the two measurement occasions. Table 3 presents the parameters computed using all available data.

The column entitled 'Uncorrected' provides the correlations between the two occasions for each of the two electrode positions. From this column, only the 1st electrode velocity parameter appears to have any significant reliability of measurement. However, perusal of Figs 3 and 4 below, showing the scatterplots of the two electrode velocity parameter values on both occasions, indicates that outlier observations are causing some instability in the reliability calculation.

On each figure, a 95% confidence ellipse has been drawn, indicating the observations that lie within a 95% confidence interval of the mean of the joint distribution of values. Recomputing the reliability coefficients, using only those observations that lie within this confidence region, indicates very high reliability of velocity measurement (as indicated in the 'Outliers removed' column of the figures). For the variability parameters there was no possibility of achieving a similar result. The parameter values were not distributed in any consistent fashion between occasions. Recomputing the correlations shown in Table 2 above, using this 'reliable' data yielded no significant changes in the pattern of correlations. However, the variability parameter correlations dropped in size to values below that sufficient for statistical significance at $P < 0.05$ one-tail.

Finally, for comparative purposes, the same reliability exercise was carried out using the data from the Barrett *et al.* (1990) study. Table 4 presents the reliability coefficients.

Figures 5 and 6 show the scatterplots of the same velocity parameters computed from this first study. Here we actually reduce the reliability parameters by removing the outlier observations (as defined by the 95% confidence region). Although the velocity parameter reliabilities are significant, they are not as high as those observed in the current study. Once again, no such manipulation was capable of being performed using the variability parameter values.

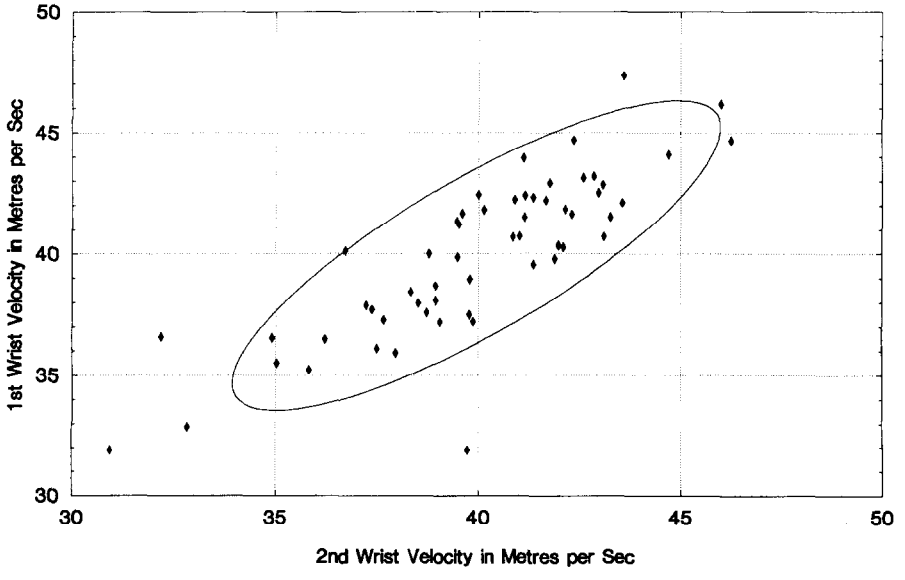

Fig. 3. Electrode 1 velocities with a 95% Gaussian Confidence region ellipse.

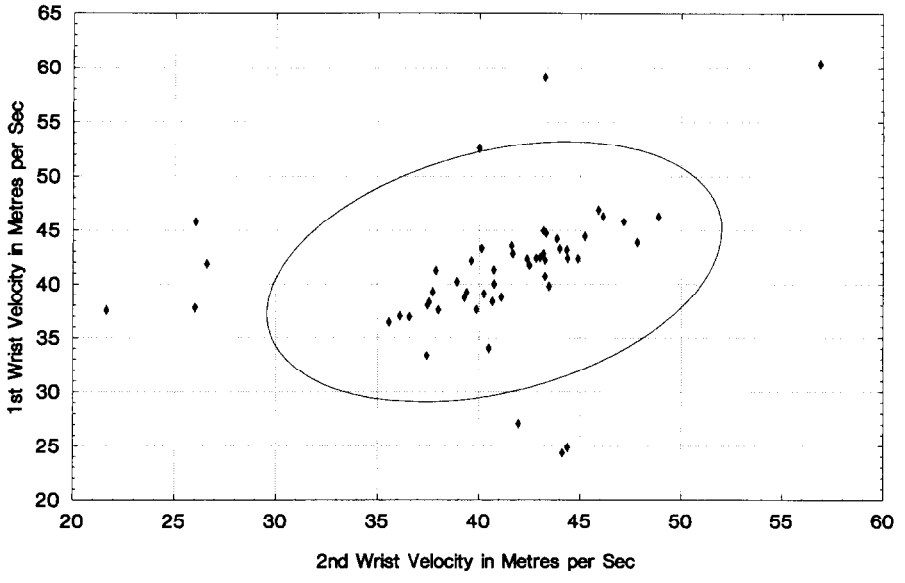

Fig. 4. Electrode 2 velocities with a 95% Gaussian Confidence region ellipse.

The correlations between EPQR Psychoticism and ASNAP velocities were all statistically insignificant one tail with all coefficients <0.10. In our first study, ASNAP velocity and EPQ Psychoticism had correlated 0.37.

DISCUSSION

From the results above, it may initially be concluded that we have mostly failed to replicate the results from our previous experiment. No consistent (across measurement occasion) significant correlation was found between measures of nerve conduction variability and IQ, or between the EPQR Psychoticism score and velocity (or variability). However, as noted in the Results section above, the distribution of IQ in this particular study was skewed toward above average ability, with very few observations below the mean full-scale IQ of 100. In our first study, we had used the Raven Advanced Progressive Matrices as a measure of IQ. In order to see how the current distribution of IQ matched that of our first study, we used some data from some previous experiments where we had collected both WAIS IQ and Ravens data on the same individuals. From the 88 *S*s available, we simply regressed WAIS full-scale IQ onto the Ravens scores (the correlation incidentally was 0.71). We then used the MAB full-scale IQ to predict Ravens scores for the 60 *S*s in this study. This indicated that the lowest predicted Ravens score in our sample was 11, the highest 24, with a mean of 17.1 and SD of 3.1. In our first study, these values were 2, 29, 14.0, and 6.8, respectively. Thus, the restriction of range in this current sample is significant. If we correct for the restriction of range in Ravens scores within the variability parameter correlations given in Table 2 above, we almost double each coefficient value within the full-scale IQ column. For the occasion 2 variability parameter correlations, these become -0.46 (from -0.23) and -0.51 (from -0.26). Both values are very similar to those observed in our first study. The problem here is whether such a correction can be justified. We simply did not observe IQs as low as those observed

Table 4. Test–retest reliability of the conduction velocity and variability parameters from Barrett *et al.* (1990)

	Uncorrected	Outliers removed
Velocity—electrode 1	0.80 (43)	0.70 (40)
Velocity—electrode 2	0.72 (43)	0.52 (36)
Variability—electrode 1	0.06 (43)	—
Variability—electrode 2	0.03 (43)	—

The figures in parentheses are the number of observations over which the correlations were computed.

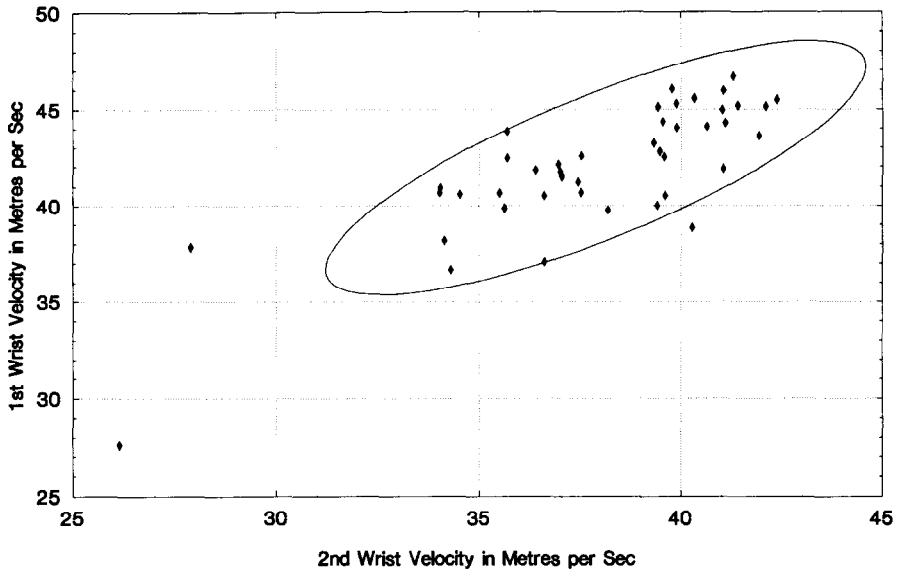

Fig. 5. Barrett *et al.* (1990) electrode 1 velocities with a 95% Gaussian Confidence region ellipse.

in our first study. From our analyses reported in Frearson, Barrett and Eysenck (1988) on the correction of correlation coefficients for the restriction of range in one measurement variable, we know that great caution must be applied to any use and interpretation of such coefficients. Note also that the correction does not boost the first occasion correlations to any level of conceptual or statistical significance.

Although we are in agreement with Reed and Jensen (1991) with regard to the failure to demonstrate any correlation between peripheral nerve conduction velocity and intelligence, the stimulus used in our studies is markedly different from that used in electromyography generally. In order to compute the variability measure as defined by Hendrickson and Hendrickson (1982), several action potential epochs are required, certainly more than the 3–10 stimulations administered by Reed and Jensen and probably more than the number administered by Vernon and Mori (1992, p. 276), who administered "as many trials as are needed to yield 8 clean averaged potentials".

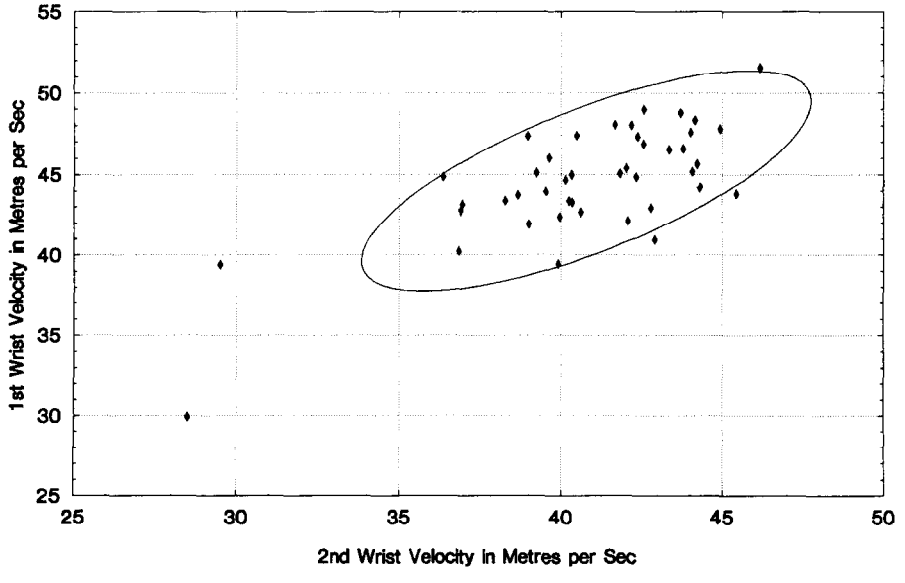

Fig. 6. Barrett *et al.* (1990) electrode 2 velocities with a 95% Gaussian Confidence region ellipse.

However, repetitive stimulation at supramaximal levels is not well tolerated by *S*s, especially over 20 trials or so. Thus, it was decided in our earlier study to use a minimal stimulus, one that was sufficient to generate a response but weak enough to yield only slight apparent sensation. Note also that in both our studies, the stimulation took place on both hands, thus doubling the number of administrations overall. The use of the 2 mA above threshold stimulus has yielded consistently slower conduction velocities than those reported in clinical electromyography generally (Oh, 1984; Ma & Liveson, 1983; Lenman & Ritchie, 1987). However, our values, consistent between hands and between studies, do fall within the lower range of expected conduction velocities for the segment of median nerve under examination. Gilliatt, Melville, Velate and Willison (1965), found that velocity differences in sensory nerves, using near-threshold and supramaximal stimulation ranged from 0.05 to 0.15 msec within 6 *S*s. The mean difference was 0.11 msec. Buchthal and Rosenfalck (1966) partially confirmed this finding, noting a 1–5% decrease in latency as the stimulating current was increased from 10 to 60 mA. If we use Gilliatt *et al.*'s findings to 'correct' our velocities, we find that our conduction velocities are very near the mean of those expected under conditions of supramaximal stimulation (55–60 m/sec). Thus, although we are not enervating the fastest conducting fibres within the nerve bundle, we are enervating the group of slower fibres in a reliable, stable, and consistent manner. Certainly, in comparison to the available test–retest coefficients noted in the Introduction above, the values we observe are as high as the one computed by Vernon and Mori and higher than that from Reed and Jensen. In addition, our coefficients are based upon sample sizes far greater than the 14 and 15 *S*s measured by the other researchers. If we propose that conduction velocity is related to intelligence, there is no *a priori* reason to assume that the relationship is mediated solely by the fastest conducting nerve fibres. Criticisms about our work, based upon the level of stimulation used, have been shown to be mistaken. We are achieving velocity parameter stability that is at least equal to that achieved using supramaximal stimulation. However, this stability is possibly harder to achieve in that we are 'losing' almost 15% of our *S*s due to measurement error. This is certainly due to the fact that we are using very low levels of stimulation.

All types of fibres should be examined to discover any possible correlations with IQ. Reed and Jensen and we agree that the type of fibre seems to make no difference, and that neither fast nor medium conduction velocity fibres show any correlation with intelligence. This agreement is important in evaluating the evidence. Vernon (1991) attributes the difference in findings between Reed and Jensen on the one hand, and himself and Mori, on the other, to a "number of methodological and procedural differences" (p. 392), but does not suggest what these might be. One significant difference is that Vernon and Mori use a longer stimulation pulse time (0.2 msec) compared to ourselves (0.1 msec) and Reed and Jensen (0.05 msec). Although the duration looks trivial, *S* perception can be sufficiently acute to perceive a significant sensation difference in this timing, albeit the shock may be at the same current intensity. *S*s report that the stimulus seems more intense (these statements are based upon our initial work with our stimulator, varying shock duration from 0.01 to 0.3 msec).

Another point of interest from our previous study and the one reported above is that we seem to be consistently observing an order effect with regard to the variability × IQ correlations. In both studies, these (uncorrected) correlations were higher for the second test occasion than the first. The effect is considerably more marked in this study than that demonstrated previously. One possible explanation for this effect is that for each *S*, electrodes were applied to both wrists simultaneously, with gel applied to the electrodes and impedance measurements made using all electrodes. Then, one particular wrist was chosen (in counterbalanced order) on which to carry out the experiment. When the procedures were finished, the other wrist electrodes were again re-checked for impedance and then used for the second occasion testing. It is possible that a slight overall lowering of impedance between the electrodes and skin surface took place on this second set, primarily due to the longer gel stabilization made possible by the testing on the other wrist. Lower impedance will yield higher quality recordings which may reflect greater sensitivity of measurement with regard to the variability parameter. Alternatively, the effect may be mediated by changes in skin conductance level at the point of stimulation (the middle finger interphalange joints). Higher skin conductance results in less voltage being applied to the body tissues in order to deliver the specified constant current. Lower applied voltage causes less shock transients, and subsequently less

transient disruption to the recorded onset of the action potential impulse. It may be that on the first occasion, skin conductance level is continually varying as a function of the possible anxiety felt during the stimulation procedure. By the time the second occasion testing is initiated, the anxiety felt by a *S* may be less and thus the conductance level is more stable, producing greater repeatability of impressed voltage level, albeit at a higher level than when skin conductance is higher.

Following on from this point is that in neither of our studies has the variability parameter achieved measurement reliability above about 0.3. Its measurement is highly unstable. The problem with this parameter is that it is sensitive to every waveform deflection, whether part of the signal or otherwise. Thus, shock transients or other stimulus related transients can cause severe degradation in the accuracy of this parameter. As noted above, changes in skin conductance can affect applied voltage levels significantly. One way around this problem is to use magnetic stimulation of the peripheral nerve (Chokroverty, 1990; Nilsson, Panizza, Roth, Basser, Cohen, Caruso & Hallett, 1992). Although there are problems in its use with respect to locating the precise source of stimulation (required for the measurement of nerve length), it does remove the problems of shock transient noise and skin conductance changes affecting applied voltage (assuming shocks are applied to the interphalangeal finger joints). In other words, a higher replicability of stimulus should be able to be achieved by this method than by using electrical stimulation. This is not because the induced stimulus is different from occasion to occasion but because the electrical voltage propagation effects of the electrically applied voltage can affect the recording of the action potential with respect to any measure of waveform variability. There can be no doubt that measuring waveform variability in electrically stimulated peripheral nerve conduction is a most difficult and intrinsically error-prone task. However, our current results to date suggest that it remains a parameter worthy of continuing investigation. As with the work examining brain evoked potential parameters and IQ (Deary & Caryl, 1992; Barrett & Eysenck, 1992), the area of study relating peripheral nerve conduction to IQ is also in a state of flux. Thus all parameters should remain targets for investigation until proven to be of trivial import.

In conclusion, this study has partially replicated our earlier work with regard to the negative correlation between conduction variability and IQ, although partially dependent upon a correction for an excessive restriction of range in the IQ scores, and the presumption of an order effect within the data. We also replicated our first study results with regard to the lack of correlation between nerve conduction velocity and IQ, but we did not replicate the correlation between EPQR Psychoticism and nerve conduction velocity. Finally, it was demonstrated that nerve conduction velocities using submaximal stimulation can be as reliable, stable, and replicable between test occasions as those computed from supramaximal stimulation of the peripheral median nerve.

REFERENCES

Barrett, P. T. & Eysenck, H. J. (1992). Brain electrical potentials and intelligence. In Gale, A. & Eysenck, M. W. (Eds), *Handbook of individual differences: Biological perspectives*. New York: Wiley.

Barrett, P. T., Daum, I. & Eysenck, H. J. (1990). Sensory nerve conduction and intelligence: a methodological study. *Journal of Psychophysiology*, *4*, 1–13.

Buchthal, F. & Rosenfalck, A. (1966). Evoked action potentials and conduction velocity in human sensory nerves. *Brain Research*, *3*, 1–122.

Chokroverty, S. (Ed.) (1990). *Magnetic stimulation in clinical neurophysiology*. Stoneham MA: Butterworth.

Deary, I. & Caryl, P. (1992). Intelligence, EEG, and evoked potentials. In Vernon, P. A. (Ed.), *Biological approaches to human intelligence*. New Jersey: Ablex.

Eysenck, H. J. & Eysenck, S. B. G. (1975). *Manual of the Eysenck Personality Questionnaire*. London: Hodder and Stoughton.

Eysenck, S. B. G., Eysenck, H. J. & Barrett, P. T. (1985). A revised version of the Psychoticism scale. *Personality and Individual Differences*, *6*, 21–29.

Eysenck, S. B. G., Pearson, P. R., Easting, G. & Allsopp, J. (1985). Age norms for impulsiveness, venturesomeness, and empathy in adults. *Personality and Individual Differences*, *6*, 613–620.

Frearson, W., Barrett, P. & Eysenck, H. J. (1988). Intelligence, Reaction Time, and the effects of smoking. *Personality and Individual Differences*, *9*, 497–517.

Gilliatt, R. W., Melville, I. D., Velate, A. S. & Willison, R. G. (1965). A study of normal nerve action potentials using an average technique (barrier grid storage tube). *Journal of Neurological and Neurosurgical Psychiatry*, *28*, 191–200.

Hegmann, J. P. (1972). Physiological function and behavioural genetics 1. Genetic variance for peripheral conduction velocity in mice. *Behavior Genetics*, *2*, 55–67.

Hegmann, J. P. (1975). The response to selection for altered conduction velocity in mice. *Biology*, *13*, 413–423.

Hegmann, J. P. (1979). A gene imposed nervous system difference influencing behavioural covariance. *Behavior Genetics*, *3*, 121–131.

Hendrickson, A. E. & Hendrickson, D. E. (1982). The biological basis of intelligence. In Eysenck, H. J. (Ed.), *A model for intelligence*. New York: Springer-Verlag.

Jackson, D. N. (1984). *The Multidimensional Aptitude Battery*. Port Huron, MI: Research Psychologists Press.

Lenman, J. A. R. & Ritchie, R. E. (1987). *Clinical electromyography* (4th Edn). London: Pitman.

Ma, D. M. & Liveson, J. A. (1983). *Nerve conduction handbook*. Philadelphia, PA: F. A. Davis.

Nilsson, J., Panizza, M., Roth, B., Basser, P., Cohen, L., Caruso, G. & Hallett, M. (1992). Determining the site of stimulation during magnetic stimulation of a peripheral nerve. *Electroencephalography and Clinical Neurophysiology*, *85*, 253–264.

Oh, S. J. (1984). *Clinical electromyography: Nerve conduction studies*. Baltimore, MD: University Park Press.

Podivinsky, F. (1967). Factors influencing the measurement of conduction velocity in the human peripheral nerve. *Journal of Neurological Science*, *5*, 493–501.

Raven, J. C. (1983a). *Manual for the Advanced Raven Progressive Matrices*. London: H. K. Lewis.

Raven, J. C. (1983b). *Manual for the Standard Progressive Matrices*. London: H. K. Lewis.

Reed, T. E. (1983). Nerve conduction velocity in mice: a new method with results and analysis of variation. *Behavior Genetics*, *13*, 257–265.

Reed, T. E. (1984). Mechanism for the heritability of Intelligence. *Nature*, *311*, 417.

Reed, T. E. & Jensen, A. R. (1991). Arm nerve conduction velocity (NCV), Brain NCV, reaction time, and intelligence. *Intelligence*, *15*, 33–47.

Reed, T. E. & Jensen, A. R. (1992). Conduction velocity in a brain nerve pathway of normal adults correlates with intelligence level. *Intelligence*, *16*, 259–272.

Rounds, G. H. (1928). Is the latent time in the achilles tendon reflex a criterion of speed in mental reactions? *Archives of Psychology*, *95*.

Travis, L. E. (1928). The correlation between intelligence and speed of conduction of the nerve impulse in a reflex arc. *Science*, *67*, 41–43.

Travis, L. E. & Hunter, T. A. (1928). The relation between 'intelligence' and reflex conduction rate. *Journal of Experimental Psychology*, *11*, 342–354.

Travis, L. E & Young, C. W. (1930). The relations of electromyographically measured reflex times in the patellar and achilles reflexes to certain physical measurements and to intelligence. *Journal of General Psychology*, *3*, 374–400.

Vernon, P. A. (1990). The use of biological meaures to estimate behavioral intelligence. *Educational Psychology*, *25*, 293–304.

Vernon, P. A. (1991). Studying intelligence the hard way. *Intelligence*, *15*, 389–395.

Vernon, P. A. & Mori, M. (1989). Intelligence, reaction times, and nerve conduction velocity [Abstract]. *Behaviour Genetics*, *19*, 779.

Vernon, P. A. & Mori, M. (1992). Intelligence, reaction times, and peripheral nerve conduction velocity. *Intelligence*, *16*, 273–288.