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STRING LENGTH, ATTENTION & INTELLIGENCE: FOCUSSED ATTENTION REVERSES THE STRING LENGTH–IQ RELATIONSHIP*

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Summary—String length of the brain evoked potentials (EPs) to an inspection time (IT) task was inversely related to IQ and mental speed as measured by the multidimensional aptitude battery IQ test and inspection time (IT) and reaction time (RT) measures of performance speed in a sample of 70 subjects. This finding is opposite to the relationship found in previous experiments, where cognitive processing was minimized. Processing efficiency and attention models were posited to account for rapid information processing accompanied by shorter string lengths among bright subjects. Nineteen channel topographic EPs from individuals differing on psychoticism (P), supported the claim that attention is a mediating variable in the string–IQ relationship. It is argued that previous experiments in this area should be reevaluated in terms of their demands on attentional resources.

INTRODUCTION

The string measure of auditory evoked potential (AEP) complexity was developed by A. E. and D. E. Hendrickson as a biological measure of intelligence. They hypothesized that differences in intelligence reflect the rate at which errors are produced during the train of neural transmissions underlying problem solving (Hendrickson, 1982a). The Hendricksons further hypothesized that variability in neural firing and the consequent variability of EEG potentials is reflected in simpler EPs with a shorter 'string length', defined as the sum of the squared Voltage differences between adjacent samples in the first 250 msec of an AEP trace generated by averaging the best 90 repetitions out of 100 presentations of a 30 msec duration 1000 Hz tone (Hendrickson, 1982b).

When applied to a digital record of the EP, string length is computed by taking the sum of the squares of differences in potential (μV) between adjacent digital samples within a certain epoch of the EP, i.e. String $= {}_{i=1}\Sigma^{i=n}(x_i - x_{i-1})^2$

Reported correlations between string and IQ have varied considerably between studies. The Hendricksons found correlations between string length, variability of the AEP and IQ in the order of $r = +0.7$ (Hendrickson, 1982b). Subsequently, similar studies have met with mixed success. While some authors have reported high correlations between string length and IQ (Stough, Nettlebeck & Cooper, 1990), others have recorded low correlations (Shagass, Roemer, Straunanis & Josiassen, 1981); others again have reported moderate correlations in the direction opposite to that predicted by the Hendricksons, even when the variability measure correlated in the expected direction (Barrett & Eysenck, 1992).

Some of these apparent contradictions may be explained by methodological deviations from the Hendricksons paradigm, for instance the use of variable and complex visual stimuli rather than identical simple tone pips (Shagass *et al.*, 1981). The question arises, then, of whether these failures to replicate show that the string measure is invalid or unreliable, or instead, reflect the influence of important but unrecognized methodological variables.

While the Hendricksons gave detailed specifications for methodological variables such as the rate at which the EEG is sampled and the precise shape of the tone waveform, some of these factors appear, in retrospect, to be immaterial. The data acquisition parameters can be identical to those

*The experimental work reported in this paper was undertaken at the Institute of Psychiatry, University of London.
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specified in the Hendricksons' 'list' without guaranteeing that the IQ–string correlation will be found (Barrett & Eysenck, 1992). On the other hand, the correlation has been replicated using a square wave pulse rather than the zero-switched sine-wave pulse specified by the Hendricksons (Stough *et al.*, 1990). It may be the case that, while the physical stimulus and data acquisition variables are relatively unimportant, psychological variables such as the level of information processing required of *S*s are of paramount importance in producing the effect. In the original Hendrickson procedure, the stimuli carried no signal value. *S*s were made quite aware that no demand would be made during, or subsequent to, the experimental session.

The present experiment was designed to assess the effect of high levels of attentional and information processing demand on the relationship between string length and IQ. If attention does affect the string length measure, this would resolve some difficulties in interpreting past research, and also provide a stimulus for new psychophysiological theories of intelligence. Inspection time (IT) was selected as a task because it demands high levels of information, processing and is also known to be a good measure of IQ (Nettelbeck & Lally, 1976; Nettelbeck, 1987). The IT task involves the tachistoscopic presentation of choice-stimuli at durations ranging downwards from around 500 msec in order to determine the minimum stimulus presentation time required for a *S* to reliably and accurately make a simple discrimination.

METHOD

Subjects

Seventy volunteer *S*s, 21 men (mean age = 32.19 years, SD = 12.02), and 49 women (mean age = 36.22 years, SD = 10.62), recruited from the local government unemployment bureau and from within the Institute of Psychiatry participated in the experiment.

Test apparatus and procedure

The IT task has been described previously (Bates & Eysenck, in press). The two target stimuli consisted of an inverted U made up of LED segments with either the left or right descender being 30% longer. To mask these stimuli, additional LED segments were lit to extend both legs of the inverted U beneath even the longest stimulus leg. On each trial a 1 kHz, 70 dB SPL warning pip sounded for 50 msec through head phones and the fixation point was lit. Following a random preparatory period of between 1 and 3 sec, one of the stimuli (chosen at random) was presented for a time determined according to an adaptive staircase procedure (Wetherill & Levitt, 1965), and was subsequently masked to prevent further inspection. Stimuli were presented with an ISI of 2 sec and a constant mask duration of 500 msec. The *S*s' task was to detect which leg of the stimulus was the shorter. Responses were made using button-press switches, held one in each hand to represent left and right hand side targets, respectively.

During the IT task, EEG was recorded from 19 standard 10–20 sites referenced to linked ears. The supra-orbital sites Fp1 and Fp2 served as eye-blink markers. All 19 channels were filtered through Butterworth 3rd order analog bandpass filters (0.8–300 Hz) and digitized synchronously with 12 bit accuracy in the range $\pm 60\,\mu V$ ($\pm 300\,\mu V$ for the Fp sites) at 1024 Hz beginning immediately prior to the IT session and continuing uninterrupted for the duration of the task.

An Electrocap™ was used to position and secure the Sn electrodes, and impedances were reduced to below 5 kΩ by gentle abrasion. Subsequently, the IT task was explained to the *S* and he/she received at least 5 practice trials with another 5 available if the *S* did not yet feel confident about the routine. At this point, the IT task was started. *S*s then worked through the adaptive IT algorithm which took approx. 7 min.

In addition to completing the IT–EEG task, *S*s also performed two reaction time tasks, the odd man out (OMO) and a three bit choice-reaction time (CRT) task. These procedures, which have also been described elsewhere (Bates & Eysenck, in press), are an application of Hick's Law to differential psychology. Hick's Law states that decision times (DTs) are in linear proportion to the number of bits of information processed per decision (Hick, 1952). A consequence of this Law is that DT can be used to index information processing rates and this technique has been applied to individual differences in intelligence (Jensen & Munro, 1979; Jensen, 1987). Both the slope of the line relating DT to information i.e. how much time is taken to process an additional bit of information, and the absolute DT have been found to correlate with IQ (Jensen, 1987). The three-bit CRT task gives a measure of DT at three bits (eight choices), while the OMO requires *S*s to make a more complex decision and has been thought to provide a less noisy measure of information processing speed than simple CRT (Frearson & Eysenck, 1986). The CRT and OMO tasks were both administered on a box with a home button around which eight lights were arranged in a semi-circle, each with a response key beneath it (Jensen & Munro, 1979). The *S* sat in front of the box and used his/her preferred hand to respond. Each trial consisted of a warning tone followed after 1–4 sec by a choice stimulus. Enough practice trials were given so that *S*s felt confident with the procedure and they then completed the experimental trials.

For CRT measurement, one of the eight possible lights was presented on each trial and *S*s had to depress the appropriate response key. Stimulus masking (Stough, Bates, Mangan & Pellett, submitted) was not used. On each OMO trial three stimulus lights were lit in a pattern arranged so that two lights were closer to each other than they were to the third, 'odd man out', stimulus. *S*s were to press the response key beneath the odd man out. In both tasks, the time for the *S* to lift his/her finger from the home button (DT) and the subsequent time to hit a response key—the *S*s' movement time (MT)—were recorded. The initial third of *S*s were given 20 trials on the CRT and OMO tasks, with the remaining *S*s completing 30 trials. This was done to examine the effect of increased trials on the reliability of RT measures; however the different number of trials did not appear to affect the results (unpaired two tailed *t*-tests show that 20 and 30 trial means did not differ significantly, $P = 0.14$ and 0.44 for CRT and OMO, respectively).

The psychometric tests (EPQ-R and Jackson Multidimensional Aptitude Battery; MAB) were administered in accordance with the directions outlined in their respective manuals (Eysenck, Eysenck & Barrett, 1985; Jackson, 1984).

EEG ANALYSIS

The continuous EEG records were decomposed into EPs to each of the warning tone and the IT stimuli with a 150 msec baseline and total EP duration of 650 msec. Trials were screened for artifact, defined as EEG amplitude $>30\,\mu V$ in either FP1 or FP2 and then low pass filtered using a 33 tap Parks-McClellan linear phase lowpass FIR (finite impulse response) filter with the stop bad maximum slope between 45 and 50 Hz. The number of artifact-free trials included in each average ranged between 100 and 75. The averaged evoked potential was then low-pass filtered with a linear phase 35 tap FIR filter with a bandpass from 0.5–40 Hz to eliminate residual high frequency noise and low frequency drift. Also, because it has previously been found that the raw amplitude of peaks is associated with personality variables such as extraversion (Haier, Robinson, Braden & Williams, 1984; Bates, Mangan & Pellett, in preparation) we removed these simple magnitude effects by normalizing the EPs to a mean of zero and a standard deviation of one. In this form, string measures complexity independently of response magnitude.

String length was computed as

$$\sqrt{\sum_{j=1}^{n}(x_j - x_{j-1})^2}$$

expressed as μV/msec, where x_j = an index into the EP array, and n is the number of samples in the EP. The square root was taken in order to return the actual length of the string rather than its square (Haier, Robinson, Braden & Williams, 1983).

String length was determined for the EP period between 0 and 300 msec. This epoch was chosen as information is certainly being processed at least until the P3 latency, while beyond this time simple stimuli have little control over the EP (as indicated by the absence of reliable peaks beyond this latency).

RESULTS

Tables of the correlations between the psychometric variables and string length computed at each channel for both the warning tone EP and for the IT–stimulus EP are shown in Tables 1 and 2. The strong relationship between performance and string is clear. A representative plot of this relationship is given in Fig. 1 which shows the individual IT–string data for the Cz electrode site.

It can be seen that the absolute magnitude of the correlations was higher for the, primarily auditory, warning–EP than was the case for correlations recorded to the visual IT–EP. Dealing first with the warning–EP data (Table 1 and Fig. 2) the following correlations stand out. IQ showed significant *negative* correlations with string length over most fronto-central sites, indicating that brighter *S*s have shorter string lengths. As might be expected given the negative relationship between speed measures and IQ, the IT, OMO and CRT data showed a significant *positive* correlation with string. The topographic distribution of the IQ, IT, and RT correlations was fronto-central with the IT data showing more involvement centrally and extending into parietal and temporal areas (see Fig. 2).

By comparison with the warning tone–EP results, the stimulus–evoked EP correlations (see Table 2 and Fig. 2) were more caudal with strong occipital involvement. This probably reflects the modality of the visual IT task.

Because the IT task demands attention (in contrast to the more typical nonattended auditory click string task), we also entered *S*s Psychoticism (P) scores into the analysis, as a measure of attention deficit has been found in high P individuals and schizophrenics (Baruch, Hemsley & Gray, 1988; Beech, Powell, McWilliam & Claridge, 1989; Eysenck, 1992; Nuechterlein, Edell, Norris & Dawson, 1986). It can be seen that P correlated with the string measure at specific sites. The warning tone generated a significant correlation at T5 while the stimulus evoked a high correlation at P4 and O1.

DISCUSSION

The present finding of an inverse relationship between mental performance and string length is opposite to previous findings made using noncognitive, auditory methods. We suggest that it is possible to reconcile this difference by reference to the *S* instructions and attentional state. One critical difference between the present study and previous experiments showing a positive

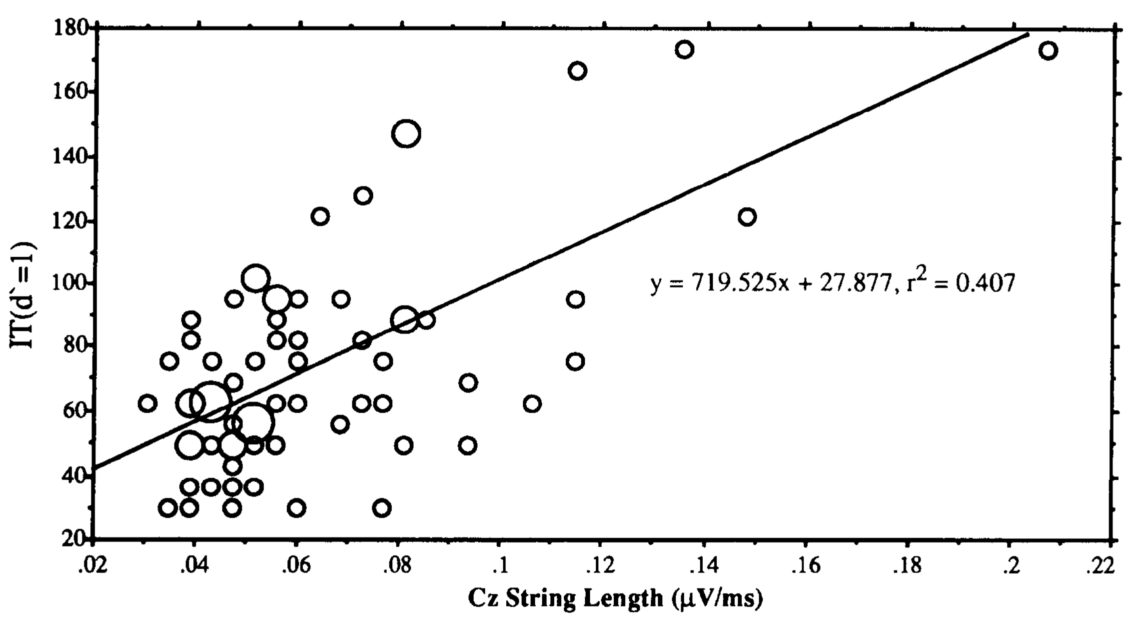

Fig. 1. Scatter plot of string length at Cz against IT. Larger symbols denote overlap of data points.

Table 1. Intelligence measures and warning tone string length

Behavioral variable	EEG channel Fp1	Fp2	F7	F3	Fz	F4	F8	C3	Cz	C4	T5	P3	P4	T6	O1	O2	T3	T4	Pz
MAB IQ	0.07	0.01	**−0.37**	−0.27	**−0.53**	**−0.61**	**−0.47**	−0.17	**−0.43**	**−0.48**	0.03	0.06	−0.26	−0.26	0.03	−0.12	0.15	**−0.35**	−0.12
IT (90%)	−0.07	−0.06	**0.38**	**0.51**	**0.62**	**0.56**	0.11	**0.68**	**0.77**	**0.62**	**0.32**	**0.49**	0.29	0.08	0.14	0.01	−0.03	0.16	**0.39**
IT(d′ = 1	−0.04	−0.04	0.23	**0.34**	**0.45**	**0.39**	0.14	**0.57**	**0.61**	**0.51**	**0.41**	**0.46**	**0.36**	0.15	0.28	0.12	−0.10	0.13	**0.40**
CRT med* DT	0.23	**0.30**	**0.48**	**0.43**	0.25	**0.36**	0.23	0.25	0.24	0.25	0.02	0.02	−0.02	−0.03	−0.16	−0.05	0.09	0.26	0.04
CRT med MT	0.13	0.13	0.05	0.04	−0.07	−0.14	−0.11	−0.15	−0.05	−0.14	0.28	−0.01	−0.17	0.02	−0.10	−0.15	−0.14	−0.13	−0.04
OMO med DT	0.02	0.07	**0.40**	**0.40**	**0.40**	**0.36**	0.14	0.23	**0.35**	**0.37**	0.24	0.07	0.08	0.10	−0.15	−0.06	0.25	0.17	0.07
OMO med MT	0.05	0.06	0.18	0.13	0.09	0.02	−0.02	−0.06	0.04	−0.03	0.35	0.06	−0.04	0.14	0.00	−0.04	0.01	−0.04	0.04
Psychoticism	0.16	0.21	−0.05	−0.01	−0.01	0.00	0.01	0.05	0.02	−0.06	**−0.31**	−0.18	−0.12	−0.27	−0.09	−0.08	−0.05	−0.18	−0.06

$N = 70$ except for IQ where $N = 60$ as some *S*s were unable to complete the test.
*med = median.

Table 2. Correlations between intelligence measures and IT stimulus string length

Behavioral variable	EEG channel Fp1	Fp2	F7	F3	Fz	F4	F8	C3	Cz	C4	T5	P3	P4	T6	O1	O2	T3	T4	Pz
MAB IQ	−0.00	0.05	−0.03	**−0.38**	−0.28	**−0.36**	**−0.50**	**−0.49**	−0.05	**−0.42**	**−0.49**	−0.16	−0.26	−0.28	−0.28	−0.07	−0.17	−0.11	−0.13
IT (90%)	−0.19	−0.04	−0.04	0.06	0.11	−0.01	0.05	0.13	0.08	**0.44**	**0.37**	**0.39**	**0.45**	**0.31**	**0.30**	0.26	**0.30**	−0.00	0.22
IT(d′ = 1)	−0.21	−0.15	−0.10	−0.04	−0.05	−0.15	−0.05	−0.00	−0.02	0.14	0.16	**0.34**	0.28	0.16	**0.42**	**0.39**	**0.37**	−0.05	0.08
CRT med* DT	−0.17	0.12	0.12	**0.32**	**0.40**	0.24	0.23	0.24	0.25	**0.52**	**0.41**	**0.44**	**0.43**	**0.32**	0.21	0.18	0.16	0.26	**0.32**
CRT med MT	−0.24	0.29	0.23	−0.11	−0.03	0.01	−0.01	−0.10	−0.23	−0.13	−0.23	0.09	−0.03	−0.16	0.07	−0.00	0.01	−0.20	−0.23
OMO med DT	**−0.30**	0.07	0.05	0.04	0.18	0.03	−0.00	0.11	0.08	**0.36**	0.28	**0.31**	**0.33**	0.23	**0.31**	0.14	0.21	0.29	0.12
OMO med MT	−0.17	0.20	0.17	−0.02	−0.01	−0.05	−0.00	−0.02	−0.15	−0.01	−0.10	0.10	0.04	−0.04	0.11	0.01	0.08	−0.10	−0.13
Psychoticism	0.07	0.13	0.18	0.08	0.01	−0.09	0.04	−0.03	−0.06	−0.12	−0.09	−0.28	**−0.30**	−0.21	**−0.34**	−0.25	−0.13	−0.19	−0.20

$N = 70$ except for IQ where $N = 60$ as some *S*s were unable to complete the test. The EP data were low pass filtered (1-35).
*med = median.

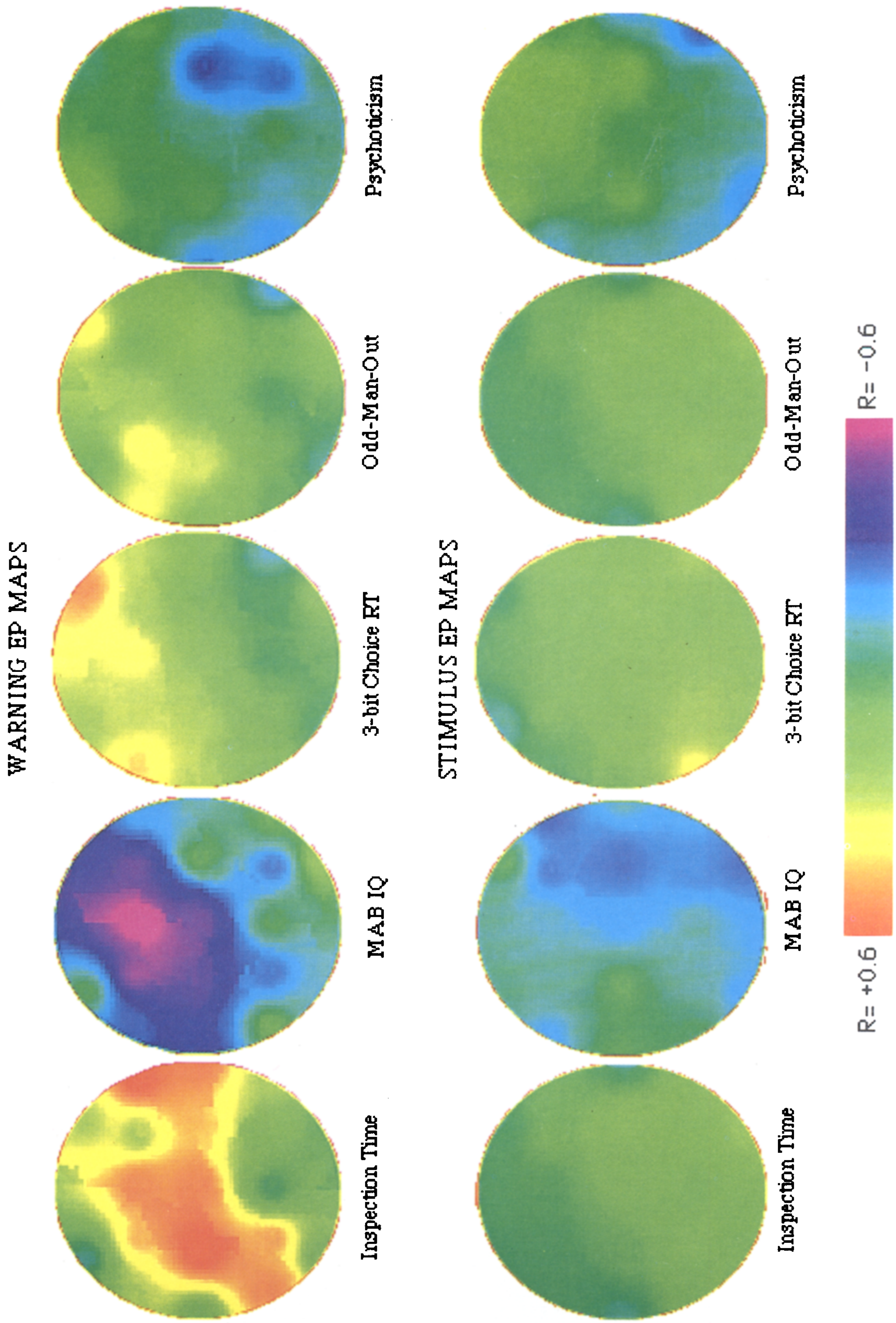
WARNING EP MAPS
Inspection Time
MAB IQ
3-bit Choice RT
Odd-Man-Out
Psychoticism
STIMULUS EP MAPS
Inspection Time
MAB IQ
3-bit Choice RT
Odd-Man-Out
Psychoticism
R= +0.6
R= -0.6

Fig. 2.

relationship between IQ and string (Hendrickson, 1982b; Stough *et al.*, 1990) is that in the present study, EPs were collected under conditions of explicit information processing demand. To the authors' knowledge, in the only other study in which a negative correlation between string and IQ has been reported (Barrett & Eysenck, 1992), *S*s were instructed to 'listen to some tones that would be presented through the headphones'. Listening, by its very nature, invokes attention. Thus, it may be important to consider the role and effect of attention in previous experiments in this area. Without a clear statement of the demands made on *S*s, it is more difficult to evaluate the string–IQ correlations in a given experiment. Very recently Birbaumer and his colleagues (Lutzenberger, Birbaumer, Flor, Rockstroh & Elbert, 1992) have reported that a dimensionality measure of EEG complexity, similar to the string length but based on chaos theory and which, under resting conditions, correlates with IQ, fails to relate to IQ when EEG sample is recorded during the performance of an imagery task. This is a further indicator that attention can alter the IQ–complexity relationship, although the imagery task employed by these workers may not have been sufficiently demanding to actually reverse the relationship as reported in the present paper.

Evidence for the hypothesis that attention controls the direction and influences the magnitude of the string length–IQ relationship may be adduced from the comparison of the warning and stimulus string correlations reported here. One would expect the pattern of correlations to differ because of the different locations and orientations of the auditory and visual cortical receiving areas. However, over and above this, it seems probable that high and moderate correlations in the warning and inspection phases of the task may reflect the different psychological activities occurring during these periods. The brain state involved in processing the warning tone may lie at one extreme of this attention-dimension, while the stimulus presentation taps a weaker form of attention. Viewed in this light, the shorter strings of bright *S*s during the warning period may reflect an ability to place the brain into a receptive 'wait-state'—poised to respond rapidly to the target IT stimulus. The fronto-central localization of the correlations, given that these areas are involved in planning and the formation of mental sets, may be considered consistent with this model. The lower correlations in the stimulus EP may then reflect a less intense phase of selective attention. This seems plausible as the target has already been located and it is the predominantly automatic processes of perception which are engaged during the stimulus–EP recording period.

If it is the case that attention can cause the string length–IQ correlation to vary so widely, then the obvious question arises—what is the relationship between string and IQ? Our theory is that string length does not index intelligence, but rather that it measures energy expended during information processing. In this way string functions as an *efficiency index* when recorded to an attended task, and as a *capacity* index when recorded under conditions of rest. The relevant variable determining which of these functions string is performing is the attentional state of the *S*.

One prediction of this theory is that in individual differences the personality variable P should affect string length via the modulation imposed on attention by P. P is related to vulnerability for several psychoses including schizophrenia (Eysenck & Eysenck, 1976; Eysenck, 1992), and there is considerable literature indicating that one of the principal diagnostic factors in psychosis is an attention deficit which may be measured in such tasks as signal discrimination (Nuechterlein *et al.*, 1986), latent inhibition (Baruch *et al.*, 1988) and negative priming (Beech *et al.*, 1989). This psychotic attention deficit may be reduced by neuroleptics (Spohn, Lacoursiere, Thompson & Coyne, 1977; Feldon & Weiner, 1991), the drug class thought to affect P (Eysenck, 1967).

To the extent that the above is true, it follows that string length at sites of the brain related to attention should vary according to levels of P. In fact the present data do show correlations between P and string length of -0.31 ($P<0.025$) over right temporal cortex for the auditory warning tone EP, and -0.30 ($P<0.025$) and -0.34 ($P<0.01$) over parietal and occipital cortex for the visual stimulus EP. These sites are superficial to primary and associative auditory and visual cortical areas, respectively. This finding that a variable known to index attentional function (Beech *et al.*, 1989) also correlates with string length supports the hypothesis that relationship between IQ and string is modulated by the attentional demands of evoking task.

The capacity–efficiency theory of string advanced here suggests that the brains of bright *S*s, relative to dull *S*s, expend more energy to unattended than to attended stimuli. If attended stimuli cease to be processed once they are 'understood' i.e. once perceptual or conceptual 'closure' occurs, then *S*s with more rapid stimulus inspection processes will generate less time-locked string activity to an attended stimulus. Contrast this with the processing of unattended stimuli. Though involving lower absolute consumption of mental resources (fewer glucose molecules), the processing of unattended stimuli may not be self terminating, as is the processing of attended stimuli. For this reason, brighter *S*s' processing of nonattended stimuli may consume more energy—generate a longer string—owing to the great capacity to expend energy in search of an informational solution. In this sense efficiency and capacity are seen as inverse properties.

Our string length–brain efficiency model of intelligence also explains two additional types of finding. Just as the present result of decreased string length in higher IQ *S*s contradicts previous reports of a positive correlation between these measures, researchers using PET measures of brain glucose energy consumption have found that the correlation between glucose metabolism and IQ is reversed between conditions of rest and active processing, respectively (De Leon, Ferris, George, Christman, Fowler, Gentes, Reisberg, Gee, Emmerich, Yonekura, Brodie, Kricheff & Wolf, 1983; Haier, Siegel, Nuechterlein, Hazlett, Wu, Paek, Browning & Buchsbaum, 1988). Data from the EEG literature modelling the brain as a complex, damped, nonlinear oscillator are also explicable by the current brain efficiency theory. High string amplitude following the destabilization provided by stimulus input in the nonattend (nondamped) condition may be thought to reflect a greater freedom to take on high frequency states i.e. capacity or band width, while attention to the stimulus will cause a dampening of oscillation as the brain settles into the low-energy equilibrium 'well' representing a consistent solution with a consequent short string length in a brain that can rapidly reach a solution. This interpretation is compatible with recent work from our own laboratory (Mangan, Pellett, Colrain & Bates, in press) and with earlier Soviet findings (Nebylitsyn, 1967, 1972) on the concept of nervous system lability, which measures the ability of the brain to respond synchronously to high frequency visual stimulation and which correlates with memory (Mangan, Bates, Pellett, Stough & Colrain, submitted).

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