PSYCHOPHYSICAL APPROACHES TO NEURAL EFFICIENCY AND PSYCHOMETRIC INTELLIGENCE: CONTRASTING THE CODING EFFICIENCY HYPOTHESIS AND THE TEMPORAL RESOLUTION POWER HYPOTHESIS.

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Abstract

A central feature of the resource consumption approach to intelligence is that individuals with above-average mental ability utilize the available neural resources more efficiently than below-average individuals. Neural efficiency has also been hypothesized to play a crucial role in perceived duration. According to the coding efficiency hypothesis, perceived duration is considered to reflect the amount of neural activity required for temporal processing of a given stimulus. As an alternative approach, the temporal resolution power (TRP) hypothesis suggests a positive functional relationship between temporal sensitivity and neural efficiency. According to the hypothesis of temporal coding efficiency, mental ability is expected to be negatively related to perceived duration, while the TRP hypothesis predicts a positive correlational relationship between temporal sensitivity and mental ability. The present study was designed to directly test the predictions derived from both these hypotheses. For this purpose, general intelligence (psychometric g) was assessed in 190 participants who also performed an auditory temporal discrimination task. In a next step, individual levels of psychometric g were correlated with psychophysical measures of perceived duration and temporal sensitivity, respectively. While there was a highly reliable positive correlation between temporal sensitivity and psychometric g, no evidence for a functional relationship between psychometric g and perceived duration could be found. The absence of a functional link between perceived duration as an indicator of coding efficiency and psychometric g suggests that coding efficiency reflects aspects of neural efficiency unrelated to psychometric intelligence. On the other hand, temporal sensitivity appears to be a valid psychophysical indicator of aspects of neural efficiency involved in psychometric g.

A central feature of the resource consumption approach to intelligence is that individuals with above-average mental ability utilize the available neural resources more efficiently than below-average individuals. Empirical evidence for this so-called neural efficiency hypothesis of intelligence comes from neuroimaging studies reporting negative correlations between psychometrically measured intelligence and cortical activation as assessed by glucose or oxygen consumption produced by tasks that draw upon these mental abilities (for concise reviews see Neubauer & Fink, 2009; Newman & Just, 2005).

Neural efficiency has also been hypothesized to play a crucial role in perceived duration of intervals in the range of tens to hundreds of milliseconds (Eagleman & Pariyadath, 2009). According to this account, perceived duration is considered to reflect the amount of neural activity required for temporal processing of a given stimulus (Eagleman, 2008; Pariyadath & Eagleman, 2007). Within the framework of the hypothesis of temporal coding efficiency, perceived duration of a stimulus is positively related to neural energy consumption. This means, the more neural energy is necessary for an individual to process the temporal information of a given stimulus, the longer the perceived duration of this stimulus will be. Thus, the physical duration of a presented stimulus should be perceived as longer by an individual characterized by low neural efficiency compared to an individual characterized by high neural efficiency. If an individual's levels of mental ability is positively related to neural efficiency and, at the same time, perceived duration of intervals in the range of milliseconds is negatively related to neural efficiency, it is reasonable to assume a negative functional relationship between mental ability and perceived duration.

An alternative hypothesis suggesting a functional relationship between neural efficiency and temporal information processing is based on the notion of an internal master clock. This concept has been introduced by Surwillo (1968) to account for age-related cognitive impairment and general slowing. He proposed an internal master clock for coordination of different mental activities. More recently, Burle and Bonnet (1999) provided additional converging experimental evidence for the existence of some kind of master clock in the human information processing system. If we assume that the hypothesized internal master clock of individual A works, for example, at half the clock rate as the one of individual B, then A does not only need twice as long as B to perform a specific sequence of mental operations, but also the occurrence probability of interfering incidents will be increased. Thus, A's lower clock rate should lead to worse mental ability compared to B.

Also human timing is often explained by the assumption of a hypothetical internal clock based on neural counting (cf., Rammsayer & Ulrich, 2001). Main features of such an internal-clock device are a pacemaker and an accumulator. The pacemaker emits pulses and the number of pulses relating to a physical time interval is recorded by the accumulator. Thus, the number of pulses counted during a given time interval is the internal representation of the interval. The higher the clock rate, the finer is the temporal resolution of the internal clock which is equivalent to higher temporal sensitivity as indicated by temporal discrimination tasks (for a concise review see Rammsayer & Brandler, 2007).

In a series of experiments, we (e.g., Helmbold, Troche, & Rammsayer, 2007; Rammsayer & Brandler, 2002, 2007) provided converging evidence for the notion that temporal sensitivity as assessed by psychophysical timing tasks may represent a valid indicator of neural efficiency underlying mental ability. More specifically, the Temporal Resolution Power (TRP) hypothesis of intelligence (Rammsayer & Brandler, 2007) proceeds from the assumption that temporal resolution capacity of the brain as assessed with psychophysical timing tasks reflects a major aspect of neural efficiency underlying mental ability. Within this conceptual framework, a positive functional relationship between temporal sensitivity and mental ability is predicted.

The present study was designed to directly test the predictions derived from the hypothesis of temporal coding efficiency and from the TRP hypothesis. According to the hypothesis of temporal coding efficiency, mental ability is expected to be *negatively* related to *perceived duration*, while the TRP hypothesis predicts a *positive* correlational relationship between *temporal sensitivity* and mental ability.

Method

Participants

Participants were 95 male and 95 female volunteers ranging in age from 18 to 39 years (mean±standard deviation of age: 25.0±5.8 years).

Intelligence tests

The aim of psychometric assessment was to obtain a valid measure of general intelligence (psychometric *g*) as an indicator of mental ability. According to Brody (1992), conclusions about psychometric *g* may be unwarranted if they are derived from psychometric intelligence tests limited to a small subset of primary mental abilities. Furthermore, Jensen (1998) emphasized that a composite score will have relatively more psychometric *g* and less specific variance if it is based on a large number of distinct mental tests. Therefore, a comprehensive test battery including 15 subtests was employed for psychometric assessment of different aspects of intelligence. The test battery was composed of several subtests (verbal comprehension, word fluency, space, flexibility of closure, perceptual speed) of the Leistungsprüfsystem (Horn, 1983). In addition, as a measure of performance on reasoning, the short version of the Culture Fair Test Scale 3 (CFT; Cattell, 1961) was applied. Individual CFT scores were obtained on the subscales Series, Classifications, Matrices, and Topologies. Eventually, our test battery comprised two subtests for numerical intelligence and three subtests for verbal, numerical, and spatial memory, respectively, of the Berliner Intelligenzstruktur-Test (Jäger, Süß, & Beauducel, 1997).

Temporal discrimination task

Stimuli were empty auditory intervals marked by a 3-msec onset and a 3-msec offset click. Clicks were white-noise bursts from a computer-controlled sound generator, presented binaurally through headphones at an average intensity of 63 dB SPL. The temporal discrimination task consisted of 64 trials, and each trial consisted of one standard interval and one comparison interval. The duration of the comparison interval varied according to an adaptive rule (Kaernbach, 1991) to estimate x.25 and x.75 of the individual psychometric function; that is, the two comparison intervals at which the response "longer" was given with a probability of .25 and .75, respectively. The standard interval was 50 msec and the initial duration of the comparison interval was 15 msec below and above the standard interval for x.25 and x.75, respectively. In each experimental block, one series of 32 trials converging to x.75 and one series of 32 trials converging to x.25 were presented. Within each series, the order of presentation for the standard interval and the comparison interval was randomized and balanced, with each interval being presented first in 50% of the trials. Trials from both series were randomly interleaved within a block. To initiate a trial, the participant pressed the space bar; auditory presentation began 900 msec later. The two intervals were presented with an interstimulus interval of 900 msec. The participant's task was to decide which of the two intervals was longer and to indicate his/her decision by pressing one of two designated keys on a computer keyboard. After each response, visual feedback ("+", i.e., correct; "-", i.e., false) was provided. As a measure of *temporal sensitivity*, the difference limen (DL) was determined. As a psychophysical indicator of *perceived duration*, the constant error (CE) was computed.

Results

As can be seen from Table 1, performances on the majority of intelligence subtests were significantly correlated with each other. In order to obtain an estimate of psychometric *g*, all psychometric test scores were subjected to a principal components analysis (PCA). The scree criterion was applied to factor extraction. PCA yielded only one factor with an eigenvalue of 4.71 that accounted for 31.4% of total variance. Factor loadings of the intelligence subscales

Table 1. Intercorrelations among intelligence subscales. (V = Verbal Comprehension, W = Word Fluency, S1 = Space 1, S2 = Space 2, C = Flexibility of Closure, P = Perceptual Speed, Ser = Series, Cla = Classifications, Mat = Matrices, Top = Topologies, N1 = Number 1, Number2 = Number 2; vM = Verbal Memory, nM = Numerical Memory, sM = Spatial Memory).

	V	W	S1	S2	C	P	Ser	Cla	Mat	Top	N1	N2	M	nM
W	.54***													
S1	.25**	.30***												
S2	.11	.28***	.42***											
C	.19**	.23***	.38***	.62***										
P	.25**	.35***	.42***	.32***	.31***									
Ser	.17*	.22**	.26**	.37***	.37***	.34***								
Cla	.19*	.21**	.18*	.31***	.28***	.15*	.19**							
Mat	.25**	.34***	.24**	.41***	.44***	.33***	.36***	.27**						
Top	.14*	.21**	.24**	.41***	.42***	.17*	.30***	.21**	.29***					
N1	.49***	.39***	.42***	.29***	.21**	.53***	.29***	.21**	.30***	.25**				
N2	.32***	.28**	.30**	.34***	.37***	.30***	.34***	.25**	.39***	.24**	.45***			
M	.24**	.17*	.13	.02	.12	.23**	.16*	.00	.10	-.07	.15*	.07		
nM	.12	.15*	.21**	.14	.11	.28***	.17*	.13	.15*	.04	.25**	.22***	.34***	
sM	-.00	.13	.23**	.34***	.31***	.21**	.23**	.26***	.26***	.17*	.09	.13	.25*	.29***

* $p < .05$; ** $p < .01$; *** $p < .001$ (two-tailed)

on the first unrotated component are shown in Table 2. This first unrotated component is commonly considered an estimate of psychometric *g* (Jensen, 1998).

Mean (±S.E.M.) temporal sensitivity, as indicated by the DL, and mean perceived duration, as indicated by CE, were 18.8±0.64 msec and 2.34±0.41 msec, respectively. While DL revealed that the mean just noticeable difference between a constant 50-msec standard and a variable comparison interval was 18.8 msec, the obtained CE indicated that mean perceived duration of the 50-msec standard interval was 52.34 msec.

Table 2. Factor loadings of intelligence scales on the first unrotated component (psychometric *g*) and communalities (h^2).

Intelligence subscale	Psychometric g	h^2
Verbal comprehension	.50	.25
Word fluency	.58	.34
Space 1	.62	.38
Space 2	.68	.46
Flexibility of closure	.67	.45
Perceptual speed	.64	.40
Series	.59	.34
Classifications	.45	.20
Matrices	.64	.41
Topologies	.50	.25
Number 1	.66	.43
Number 2	.62	.39
Verbal memory	.28	.08
Numerical memory	.39	.15
Spatial memory	.43	.19

Correlational analyses yielded a statistically significant correlation coefficient of r=.36 between temporal sensitivity and psychometric g (p<.001). On the other hand, the correlation coefficient of r=-.12 (p=.11) between perceived duration and psychometric g failed to reach the 5% level of statistical significance. The difference between these two correlation coefficients was highly significant (z=3.53, p<.001). Because temporal sensitivity and perceived duration were significantly correlated with each other (r=-.51, p<.001), additional partial correlations were computed. When controlling for perceived duration, the correlation between temporal sensitivity and psychometric g remained virtually unchanged (r=.35, p<.001). Controlling for temporal sensitivity, however, further decreased the non-significant correlation between perceived duration and psychometric g from r=-.12 to r=-.08.

Discussion

Obviously, variation in individual levels of psychometric g is linked to aspects of information processing capacity (cf., Jensen, 1998; 2006; Sheppard & Vernon, 2008). To date, however, little is known about the basic biological mechanisms by which this is achieved. Proceeding from the general assumption that psychometric g is a function of the central nervous system to process information quickly and correctly, different biological phenomena have been introduced as prime candidates for a biological basis of psychometric g: Neuronal refractory periods, reliability of neuronal transmission, neural pruning, myelination of neurons, or differences in neural plasticity. On the whole, all these accounts refer to neural efficiency in the brain as a basic determinant of individual differences in psychometric g (Neubauer & Fink, 2009).

These biological approaches to psychometric intelligence can be translated into at least two theoretical accounts related to temporal information processing. According to the coding efficiency hypothesis (Eagleman & Pariyadath, 2009), neural energy expenditure is positively related to perceived duration. More precisely, perceived duration is considered to reflect the amount of neural activity required for temporal processing of a given stimulus (Eagleman, 2008; Pariyadath & Eagleman, 2007). If neural efficiency is involved in both psychometric g and coding efficiency, then a *negative* correlational relationship between individual levels of psychometric g and perceived duration would be the expected outcome. This is because higher neural efficiency should result in higher psychometric intelligence and shorter perceived duration.

On the other hand, the TRP hypothesis of psychometric intelligence (Rammsayer & Brandler, 2007) predicts finer temporal resolution capacity of the brain as a psychophysical correlate of neural efficiency underlying psychometric g. Within this conceptual framework, a *positive* functional relationship between temporal sensitivity and psychometric intelligence could be expected.

Our finding of a non-significant correlation between psychometric g and perceived duration clearly argues against the validity of the coding efficiency hypothesis. At the same time, the statistically significant positive relationship between temporal sensitivity and psychometric g supports the TRP hypothesis of psychometric intelligence. Given these results, temporal sensitivity appears to be a valid psychophysical indicator of aspects of neural efficiency involved in psychometric g. The absence of a functional link between perceived duration, as an indicator of coding efficiency, and psychometric g suggests that coding efficiency reflects aspects of neural efficiency unrelated to psychometric intelligence.

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