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Temporal Information Processing and Pitch Discrimination as Predictors of General Intelligence

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Abstract In the present study, the relationship between performance on temporal and pitch discrimination and psychometric intelligence was investigated in a sample of 164 participants by means of an experimental dissociation paradigm. Performance on both temporal and pitch discrimination was substantially related to psychometric intelligence (r = .43 and r =.39). Regression analysis and structural equation modeling suggested that both psychophysical domains can be considered as valid predictors of psychometric intelligence. Both predictor variables contributed substantial portions of both shared and unique variance to the prediction of individual differences in psychometric intelligence. Thus, the present study yielded further evidence for a functional relationship between psychometric intelligence and temporal as well as pitch discrimination acuity. Eventually, findings are consistent with the notion that temporal discrimination – in addition to general aspects of sensory discrimination shared with pitch discrimination – reflects specific intelligence-related aspects of neural information processing.

Résume Dans la présente étude, la relation entre l'intelligence psychométrique et les rendements à la discrimination temporelle et à la discrimination des hauteurs tonales a été étudiée auprès de 164 participants à l'aide d'un paradigme de dissociation expérimentale. Les rendements à la discrimination temporelle et à la discrimination des hauteurs tonales ont pu être liés de façon substantielle à l'intelligence psychométrique (r = ,43 et r = ,39). L'analyse de régression et la modélisation de l'équation structurelle suggèrent que les deux domaines psychophysiques peuvent être considérés comme des prédicteurs valides de l'intelligence psychométrique. Les deux variables psychophysiques contribue de manière importante à la variance partagée et unique dans la prédiction des différences individuelles de l'intelligence psychométrique. Ainsi, l'étude soutient l'idée qu'il existe une relation fonctionnelle entre l'intelligence psychométrique et l'acuité de la discrimination temporelle et de la hauteur tonale. Les conclusions concordent avec la notion que la discrimination temporelle - en plus des aspects généraux de la discrimination sensorielle partagée avec la discrimination de la hauteur tonale - reflète des aspects du traitement de l'information neurale qui sont liés à l'intelligence spécifique.

During the last three decades, the mental speed approach to human intelligence has produced converging evidence for a linear relationship between efficiency and speed of information processing in so-called "elementary cognitive tasks" (ECTs) and psychometric intelligence (see Deary, 2000; Neubauer, 1995, 1997; Schweizer, 2005; Vernon, 1987). Various measures of speed of information processing, such as simple and choice reaction time following the rationale of Hick (1952; for reviews see Jensen, 1987, 1998), inspection time (Brand & Deary, 1982; Vickers, Nettelbeck, & Wilson, 1972), short-term memory scanning (Sternberg, 1966, 1969), or long-term memory retrieval (Posner & Mitchell, 1967), have been found to be associated with higher psychometric intelligence.

Several attempts have been made to describe the physiological basis of individual differences in speed and efficiency of the information processing system and its association to psychometric intelligence. Biological approaches to human intelligence usually refer to the concept of "neural efficiency" in the brain as a basic determinant of individual differences in cognitive abilities (Bates, Stough, Mangan, & Pellett, 1995; Neubauer, 2000; Sternberg & Kaufmann, 1998; Vernon, 1993). Against the background of this concept, the relationship between intelligence and speed of information processing has been explained by different approaches such as reliability of neuronal transmission (Hendrickson, 1982; Hendrickson & Hendrickson, 1980), specific cortical activation (Neubauer, Freudenthaler, & Pfurtscheller, 1995; Neubauer, Schrausser, & Freudenthaler, 2000), neural pruning (Haier, 1993), myelination of neurons (Miller, 1994), neural adaptability (Schafer, 1979, 1982, 1985), or differences in neural plasticity (Garlick, 2002).

In his model of neuronal oscillations, Jensen (1982) proposed that individual differences in processing speed and psychometric intelligence can be attributed to differences in the rate of oscillation between refractory and excitatory states of neurons or groups of neurons. A high oscillation rate is supposed to allow a faster and more efficient transmission of neurally encoded information, since it will take less time for a neuron to enter the excitatory phase of its cycle when a stimulus is presented during the refractory state as for a neuron with slow oscillation rate. According to this view, individuals with fast neuronal oscillation rate should process information faster and as a consequence show better performance on ECTs and intelligence tests.

An alternative but similar metaphor that also refers to a hypothetical oscillatory process in the human central nervous system (CNS) to account for the relationship between efficiency and speed of information processing and intellectual capacity has been put forward by Surwillo (1968). According to his so-called master clock metaphor, high temporal resolution power of the CNS should allow a higher speed of information processing as the same sequence of mental operations can be processed in a shorter period of time. Concurrently, less time required for performing a specific sequence of mental operations might also decrease the occurrence probability of interfering incidents (cf. Lindenberger, Mayr, & Kliegl, 1993; Rammsayer & Brandler, 2002; Salthouse, 1991). Eventually, this should lead to a higher efficiency of information processing as, for instance, indicated by superior performance on tests for psychometric assessment of intelligence (cf. Rammsayer & Brandler, 2002, 2005).

In order for the temporal resolution power hypothesis to receive serious consideration, it has to be demonstrated that some measure of temporal resolution power is reliably associated with psychometric intelligence. Rammsayer and Brandler (2002, 2005) proceeded from the notion that psychophysical measures of timing accuracy and temporal sensitivity might represent one of the most direct measures of temporal resolution power of the CNS. In a first study, Rammsayer and Brandler (2002) investigated the relationship between general fluid intelligence as indicated by Cattell's Culture Fair Intelligence Test Scale 3 (CFT; Cattell, 1961) and different measures of temporal information processing performance. An exploratory principal components analysis yielded a first unrotated component strongly related to performance on interval discrimination in the range of seconds and milliseconds, temporal order judgment, and CFT. The fact that measures of psychometric intelligence and psychophysical timing performance exhibited substantial loadings on a common general factor appears to be consistent with the existence of a latent variable accounting for individual differences in both psychometric intelligence and temporal information processing, respectively.

In a more recent study, Rammsayer and Brandler (2005) assessed the performance on eight different temporal tasks and 15 intelligence tests allowing factor analytic extraction of the first unrotated component for each aspect of performance, referred to as psychometric *g* and temporal *g*, respectively. Correlational analysis yielded a reliable association between psychometric *g* and temporal *g* (r = .56). Additional stepwise multiple regression analysis revealed that performance on temporal information processing provided a more valid predictor of psychometric *g* than traditional reaction time parameters derived from the Hick paradigm.

Rammsayer and Brandler (2002, 2005) interpreted their findings as supporting evidence for the validity of the temporal resolution power hypothesis to account for individual differences in mental capacity and speed of information processing. Their results are consistent with the notion that accuracy of timing performance represents a valid and sensitive behavioural indicator of the temporal resolution capacity of the CNS presumed to reflect an essential aspect of neural efficiency.

When, however, considering the fact that duration represents a qualitative stimulus characteristic, such as colour, brightness, pitch, or size, and that all timing tasks employed by Rammsayer and Brandler (2002, 2005) required some kind of temporal discrimination performance, an alternative explanation for the observed relationship between timing performance and psychometric intelligence may refer to the significance of rather unspecific sensory discrimination capacity as the decisive factor linking psychophysical performance to psychometric intelligence. The possibility that there is a relationship between intelligence and sensory-perceptual processing is an old idea, which can be traced back to Galton's (1883) hypothesis of a functional relationship between individual differences in mental capacity and fine-tuned differences in sensory discrimination. He based his idea on the argument that "the only information that reaches us concerning outward events appears to pass through the avenue of our senses; the more perceptive the senses are of differences, the larger is the field upon which our judgement and intelligence can act" (Galton, 1883, p. 19). Also, Spearman's (1904) early research was characterized by a similar approach. He presumed the existence of a near-perfect correspondence between "any common and essential element in Intelligences" (p. 269) referred to as General Intelligence and "any common and essential element in the Sensory Functions" (p. 269) referred to as General Sensory Discrimination.

It should be noted, however, that the empirical work of Galton (1883, 1908) and most subsequent studies (e.g., Cattell, 1890; Cattell & Farrand, 1896; Sharp, 1898/1899; Wissler, 1901) failed to reveal any meaningful connection between judgments of intelligence and sensory measures and Spearman's scientific interest soon took a new direction. As a consequence, this account lay dormant for several decades. In a re-evaluation of these early studies, however, Deary (1994a) arrived at the conclusion that the widely held current view about the failure of these historical attempts to relate intelligence to the senses was incorrect because it was based upon inaccurate reports of few poorly conducted negative studies and the omission of positive findings from other research.

Since the 1970s, Galton's (1883) and Spearman's (1904) hypotheses have been resurrected within the information processing framework of intelligence (cf. Deary, 1994a; Deary, Bell, Bell, Campbell, & Fazal, 2004; Li, Jordanova, & Lindenberger, 1998; Raz, Willermann, Ingmundson, & Hanlon, 1983; Raz, Willermann, & Yama, 1987). For most qualitative dimensions of sensory stimuli such as colour or shape in the visual modality (e.g., Deary et al., 2004; Schweizer & Koch, 2003; Schweizer, Zimmermann, & Koch, 2000), pitch, loudness, or spatial location in the auditory modality (e.g., Deary, 1994b; Deary et al. 2004; Lynn, Wilson, & Gault, 1989; McCrory & Cooper, 2005; Raz et al., 1987; Watson, 1991), and pressure, shape or texture in the tactile modality (e.g., Li et al., 1998; Roberts, Stankov, Pallier, & Dolph, 1997), moderate correlational relationships between sensory discrimination performance and psychometrically assessed intelligence have been reported. Nevertheless, authors such as Acton and Schroeder (2001) emphasize that these correlational relationships should not be overrated and refer to studies that yielded rather ambiguous results (cf. Deary, Head, & Egan, 1989; Stankov, Seizova-Cajić, & Roberts, 2001).

Hence, the question arises whether the association between psychometric intelligence and temporal information processing reported by Rammsayer and Brandler (2002, 2005) is due to the fact that timing accuracy directly reflects a specific neural property as suggested by the temporal resolution power hypothesis or whether it must primarily be attributed to the more general functional relationship between mental capacity and sensory discrimination ability. As a critical test for this question, in the present study, an experimental dissociation paradigm developed by Gibbons, Brandler, and Rammsayer (2002) was applied. This task permits a direct contrast between the relationship of psychometric intelligence and temporal discrimination, on the one hand, and psychometric intelligence and pitch discrimination, on the other. This paradigm includes both a temporal discrimination and a pitch discrimination task. The crucial feature of this procedure is that both tasks present the same set of stimuli in order to exclude stimulus-specific influences on discrimination performance.

The decision to contrast temporal with pitch discrimination was based on the following considerations. First, temporal discrimination tasks usually examine auditory stimuli because the auditory modality shows finer temporal resolution than other modalities (cf. Goodfellow, 1934; Grondin, 1993; Grondin, Meilleur-Wells, Ouellette, & Macar, 1998; N'Diaye, Ragot, Garneo, & Pouthas, 2004; Schab & Crowder, 1989). Thus, another auditory stimulus dimension had to be chosen to allow for a direct comparison on the basis of the same set of stimuli. We explicitly decided to use pitch discrimination rather than other auditory discrimination abilities such as loudness discrimination or spatial location of tones. This decision was motivated by the fact that pitch discrimination seems to represent the most intensively investigated sensory correlate of psychometric intelligence that yielded fairly consistent results. Most studies investigating the relationship between performance on pitch discrimination and psychometric intelligence reported correlation coefficients typically varying in the range from r = .20 to r = .40 (e.g., Acton & Schroeder, 2001; Bazana & Stelmack, 2002; Bentley, 1963; Deary, 1994b; Irwin, 1984; Lynn & Gault, 1986; Lynn et al., 1989; Olsson, Björkman, Haag, & Juslin, 1998; Raz, Moberg, & Millman, 1990; Raz et al., 1983, 1987; Watson, 1991).

Based on this experimental approach, the present study intended to further investigate the relationship between psychometric intelligence, on the one hand, and pitch and temporal discrimination, on the other. In a first step, pitch and temporal discrimination should be shown to represent valid indicators of psychometric intelligence. Then, in a second step, the unique contributions of both psychophysical domains to the prediction of psychometric intelligence should be analyzed more precisely. With regard to this objective, we made the following assumptions: If the relationship between timing accuracy and psychometric intelligence is primarily due to a general relationship between mental capacity and accuracy of sensory processing, both kinds of discrimination performance would not be expected to provide substantial unique contributions to the prediction of psychometric intelligence. This is because in this case temporal and pitch discrimination would be supposed to predominantly represent the same source of intellectual variance. On the other hand, if timing performance does not only reflect an aspect of general sensory discrimination but also represents a valid indicator of some special kind of temporal resolution power of the brain, then temporal discrimination should provide a unique contribution to psychometric *g* unrelated to pitch discrimination.

Method

Participants

Participants were 82 male and 82 female volunteers ranging in age from 18 to 34 years (mean ± standard deviation of age: 23.3 ± 4.2 years). The sample com-

TABLE 1
Description of the Psychometric Tests Applied for Measuring Primary Mental Abilities

Intelligence test	Subscale/Ability	Task characteristics
LPS	Verbal Comprehension	Detection of spelling mistakes in nouns
LPS	Word Fluency	Anagrams
LPS	Space 1	Mental rotation
LPS	Space 2	Three-dimensional interpretation of two-dimensionally presented objects
LPS	Flexibility of Closure	Detection of single elements in complex objects
LPS	Perceptual Speed	Comparison of two columns of letters and digits
CFT	Series	Completion of a series of pictures
CFT	Classifications	Finding two pictures that violate a rule within a set of five pictures
CFT	Matrices	Completion of a matrix
CFT	Topologies	Topological reasoning
BIS	Number 1	Detection of numbers exceeding the preceding number by "three"
BIS	Number 2	Solving of complex mathematical problems by means of simple mathematical principles
BIS	Verbal Memory	Reproduction of previously memorized nouns
BIS	Numerical Memory	Reproduction of two-digit numbers
BIS	Spatial Memory	Recognition of buildings on a city map

Note: The scales are listed in the order of their presentation. (LPS = Leistungsprüfsystem; CFT = Culture Fair Test Scale 3; BIS = Berliner Intelligenzstruktur-Test).

prised 48 university students, 15 academics, 76 grammar or vocational school pupils and apprentices, 20 nonacademic working people as well as 5 persons who were unemployed. Participants were recruited via information talks or announcements posted at notice-boards at the Georg August University, Göttingen, and various schools as well as adult education centres. For taking part in the study, they were paid the equivalent of US$30 and offered feedback about their performance on intelligence testing. All participants reported normal hearing and had normal or corrected-to-normal sight.

Intelligence Tests

The aim of psychometric assessment in the present study was to obtain a valid measure of psychometric *g*. 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 corresponding to Thurstone's (1938) primary mental abilities. Intelligence data obtained by this battery should finally allow estimation of psychometric *g* by means of a hierarchical factor analysis (Jensen, 1998; Jensen & Weng, 1994).

The test battery was, in part, composed of several subtests (Verbal Comprehension, Word Fluency, Space, Flexibility of Closure, Perceptual Speed) of the Leistungsprüfsystem (LPS; Horn, 1983), a German intelligence test based on Thurstone's (1938) model of primary mental abilities. In addition, as a measure of performance on reasoning, the short version of the German adaptation of Cattell's Culture Fair Intelligence Test Scale 3 (CFT; Cattell, 1961) by Weiß (1971) was applied. Individual CFT test scores were obtained on the subscales Series, Classifications, Matrices, and Topologies. The last part of the test battery consisted of two subtests for numerical intelligence and three subtests for verbal, numerical, and spatial memory, respectively, of the Berliner Intelligenzstruktur-Test (BIS; Jäger, Süß, & Beauducel, 1997).

All intelligence tests were combined speed-power tests. Instructions were given directly before the application of the respective test. A brief description of the psychometric tests is presented in Table 1.

Auditory Discrimination Tasks

The comparison of temporal and pitch discrimination was realized by the use of an experimental dissociation paradigm developed by Gibbons et al. (2002). This paradigm includes a pitch and a temporal discrimination task based on an identical set of auditory stimuli. The tasks only differed with regard to the respective instruction given at the beginning of the task in which the participant was asked to either judge duration or pitch of the presented tones.

Apparatus and Stimuli

The presentation of the stimuli and the recording of the participants' responses were controlled by a computer. The stimuli were sine waves presented through headphones (SONY CD 450) at an intensity of 67 dB. The tones varied on the two stimulus dimensions, pitch and duration, simultaneously. Seven levels of pitch

TABLE 2
Frequency Distribution of Stimuli in the Stimuli Set Presented Within the Dissociation Paradigm

	Stimulus Duration							
Pitch	125 ms	150 ms	175 ms	200 ms (standard)	225 ms	250 ms	275 ms	Σ
964 Hz	1	1	1	3	1	1	1	9
976 Hz	1	1	1	3	1	1	1	9
988 Hz	1	1	1	3	1	1	1	9
1,000 Hz (standard)	3	3	3	9	3	3	3	27
1,012 Hz	1	1	1	3	1	1	1	9
1,024 Hz	1	1	1	3	1	1	1	9
1,036 Hz	1	1	1	3	1	1	1	9
Σ	9	9	9	27	9	9	9	81

were designed: 964 Hz, 976 Hz, 988 Hz, 1,000 Hz (= standard), 1,012 Hz, 1,024 Hz, and 1,036 Hz. Likewise, stimulus duration was also varied on seven levels: 125 ms, 150 ms, 175 ms, 200 ms (= standard), 225 ms, 250 ms, and 275 ms.

The decision for these stimulus durations was based on two considerations. First, use of strategies should be avoided as far as possible. With longer intervals, the probability increases that participants use counting to improve the precision of their timing (Fettermann & Killeen, 1992; Getty, 1976; Grondin, Meilleur-Wells, & Lachance, 1999). Furthermore, levels of both stimulus dimensions were chosen on the basis of the results of a pilot experiment conducted to identify comparable levels of difficulty in both tasks (cf. Gibbons et al., 2002).

Design of the set of stimuli underlying both tasks was based on the following requirements: 1) for pitch as well as for duration, there should be a probability for the standard stimulus of .33 in the total number of trials, 2) within each level of one stimulus dimension, each level of the respective other stimulus dimension should be represented, and 3) also for each of the seven levels of one stimulus dimension, there should be a probability of .33 for the occurrence of the standard stimulus of the respective other stimulus dimension. Simultaneous variation of both stimuli dimensions according to these requirements resulted in a stimuli set of 81 stimuli based on the frequency distribution presented in Table 2.

Procedure

An experimental session comprised one temporal discrimination task and one pitch discrimination task. The order of tasks was counterbalanced across participants. Both tasks consisted of two phases, a learning phase and a test phase. Each test phase was initiated by five practice trials to ensure that the participants understood the instructions and to familiarize them with the stimuli. Practice trials were not included in statistical analyses.

Temporal discrimination. Participants were required to identify a standard stimulus duration of 200 ms among a set of six nonstandard intervals with deviant durations (125 ms, 150 ms, 175 ms, 225 ms, 250 ms, and 275 ms). In the first part of the task, the learning phase, participants were instructed to memorize the standard stimulus duration. For this purpose, the standard interval of 200 ms was presented five times with a pitch (900 Hz) not administered in the test period. After the learning phase, participants were asked to start the test trials by pressing the space key of a computer keyboard. On each test trial, one duration stimulus was presented. A trial began with the presentation of a fixation point in the centre of the computer screen. After a foreperiod of 1,000 ms, the auditory stimulus was presented while the fixation point remained on the screen. Participants were instructed to attend solely to stimulus duration and to ignore the pitch of the stimuli. Their task was to decide whether or not the presented stimulus was of the same duration as the standard stimulus stored in memory and to indicate their decision by pressing one of two designated response keys ("standard" vs. "nonstandard"). After each response, a visual feedback ("+", i.e., correct; "-", i.e., false) was displayed for 500 ms on the computer screen. The next trial started immediately after the feedback. The test phase comprised 81 trials, including 27 presentations of the standard and nine presentations of each nonstandard interval (see Table 2). The presentation order of the stimuli was pseudo-randomized, with the restriction of no more than two successive presentations of the standard stimulus.

As a quantitative measure of performance on temporal discrimination, an individual index of response dispersion (cf. Wearden, Wearden, & Rabbitt, 1997) was computed. For this purpose, the sum of the relative frequencies of "standard" responses to the standard duration (200 ms) and the two immediately adjacent nonstandard durations (175 ms and 225 ms) was divided by the sum of the relative frequencies of "standard"

TABLE 3
Mean (M), Standard Error of the Mean (S.E.M.), Minimum (Min), and Maximum (Max) of All Performance Measures Obtained.

Performance measure	*M*	*S.E.M.*	*Min*	*Max*
Intelligence tests				
Verbal Comprehension	22.3	.50	8	38
Word Fluency	28.5	.62	5	40
Space 1	22.1	.57	5	40
Space 2	29.0	.45	8	39
Flexibility of Closure	32.2	.43	15	40
Perceptual Speed	24.7	.40	13	35
Series	7.5	.11	4	11
Classifications	6.6	.15	1	12
Matrices	6.5	.13	1	10
Topologies	5.6	.13	0	10
Number 1	21.8	.58	1	40
Number 2	3.8	.17	0	7
Verbal Memory	8.0	.18	3	15
Numerical Memory	7.4	.16	2	12
Spatial Memory	15.7	.36	4	26
Auditory discrimination tasks				
Temporal Discrimination	.74	.01	.34	1.00
Pitch Discrimination	.69	.01	.37	1.00

Note: Scores on intelligence tests were determined by the number of items correctly solved. As performance measure on temporal and pitch discrimination the individual index of response dispersion was employed.

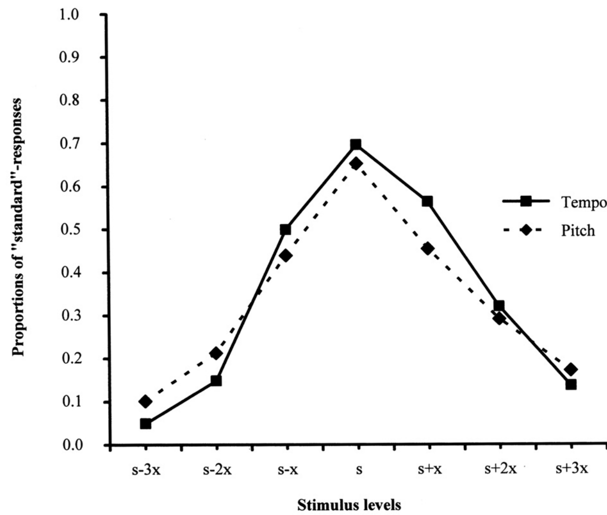

Figure 1. Discrimination functions for temporal and pitch discrimination.
Note: Both functions represent the mean percentage of "standard"-judgments as a function of the seven stimulus levels for duration and pitch discrimination, respectively. For temporal and pitch discrimination, *s* indicates the standard duration (200 ms) and the standard pitch (1,000 Hz), respectively. With regard to stimulus level, *x* represents a basic step size of 25 ms for temporal discrimination and 12 Hz for pitch discrimination. Resulting stimulus levels were 125 ms, 150 ms, 175 ms, 200 ms (= standard), 225 ms, 250 ms, and 275 ms for temporal discrimination and 964 Hz, 976 Hz, 988 Hz, 1,000 Hz (= standard), 1,012 Hz, 1,024 Hz, and 1,036 Hz for pitch discrimination.

responses to all seven stimulus durations presented.[1] This measure would approach 1.0 if all "standard" responses were clustered closely around the standard duration.

Pitch discrimination. The pitch discrimination task was based on the same psychophysical procedure and the same set of stimuli as the temporal discrimination task. The tasks just differed with respect to the participant's instruction. In the pitch discrimination task, participants were asked to decide whether or not the presented stimulus was of the same pitch as the standard tone (1,000 Hz) and to ignore the duration of the stimulus. Thus, the learning phase of the pitch discrimination task included five presentations of a 1,000 Hz-tone, which had to be memorized as standard pitch. The duration of the standard tone (260 ms) presented during the learning phase was not included in the stimuli set presented in the subsequent test phase. Just as in the temporal discrimination task, individual indices of response dispersion were determined as a measure of performance on pitch discrimination.

Time Course of the Study

Order of testing was counterbalanced across participants. For half of the participants, the auditory discrimination tasks were preceded by psychometric assessment of intelligence, while for the other half, intelligence tests were administered after the discrimination tasks.

Results

Descriptive statistics of the observed values of all performance measures obtained in the present study are presented in Table 3. Figure 1 shows the average discrimination functions for the duration and the pitch discrimination tasks. The graphs represent the mean percentage of "standard" judgments as a function of the seven stimulus levels for duration and pitch discrimination, respectively. Both psychophysical functions peaked at the standard duration. The graph for temporal discrimination was slightly steeper than the one for pitch discrimination.

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[1] Formula used to calculate the dispersion index:

$$\frac{p(S \mid s\text{-}x) + p(S \mid s) + p(S \mid s\text{+}x)}{p(S \mid s\text{-}3x) + p(S \mid s\text{-}2x) + p(S \mid s\text{-}x) + p(S \mid s) + p(S \mid s\text{+}x) + p(S \mid s\text{+}2x) + p(S \mid s\text{+}3x)}$$

p = relative frequency; S = "standard"-response; s = standard stimulus;
x = basic step size in variation of stimulus level

TABLE 4
Intercorrelations Among Subscales of Mental Abilities

	V	W	S1	S2	C	P	Ser	Cla	Mat	Top	N1	N2	vM	nM
W	.55***													
S1	.23**	.31***												
S2	.09	.29***	.41***											
C	.18*	.27***	.36***	.63***										
P	.25**	.35***	.40***	.31***	.30***									
Ser	.20*	.27**	.26**	.42***	.38***	.38***								
Cla	.19*	.23**	.19*	.31***	.28***	.16*	.24**							
Mat	.25**	.35***	.26**	.41***	.45***	.33***	.42***	.26**						
Top	.11	.21**	.23**	.40***	.40***	.17*	.35***	.20**	.30***					
N1	.50***	.38***	.42***	.30***	.24**	.54***	.31***	.24**	.33***	.25**				
N2	.28***	.26**	.28**	.33***	.40***	.30***	.39***	.24**	.41***	.23**	.46***			
vM	.26**	.19**	.14	.02	.12	.26**	.16*	.02	.13	-.11	.14	.09		
nM	.16*	.16*	.23**	.16	.19	.31***	.20**	.16*	.21**	.04	.23**	.28***	.35***	
sM	-.00	.13	.24**	.35***	.30***	.21**	.24**	.30***	.29***	.15	.11	.17*	.23	.33***

* $p < .05$; ** $p < .01$; *** $p < .001$ (two-tailed).
Note: (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, N2 = Number 2, vM = Verbal Memory, nM = Numerical Memory, sM = Spatial Memory).

TABLE 5
Factor Pattern Matrix of Intelligence Scales

	Factor			Communality
Intelligence Scale	I	II	III	h^2
Space 2	**.82**	-.09	-.02	.62
Verbal Comprehension	-.08	**.76**	.02	.56
Number 1	.21	**.62**	.03	.55
Flexibility of Closure	**.73**	-.03	.03	.54
Word Fluency	.18	**.53**	.03	.40
Perceptual Speed	.23	**.33**	.26	.39
Matrices	**.51**	.15	.08	.38
Verbal Memory	-.17	.14	**.60**	.38
Numerical Memory	.07	.04	**.57**	.38
Spatial Memory	.38	-.24	**.45**	.38
Series	**.49**	.12	.09	.35
Topologies	**.59**	.05	-.23	.34
Number 2	**.39**	.26	.07	.33
Space 1	**.35**	.22	.13	.29
Classifications	**.37**	.06	.05	.17

TABLE 6
Results of Standard Multiple Regression Analysis

Predictor variables	B	β	*t* value	sr_i^2 (unique)
Temporal discrimination	2.09	.323	4.30***	.087
Pitch discrimination	1.45	.264	3.51**	.058
				$R = .494$
				$R^2 = .244$***

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

All psychometric test scores were subjected to a hierarchical factor analysis to obtain a valid estimate of psychometric *g*. As can be seen from Table 4, performances on the majority of intelligence subtests were significantly correlated with each other. Thus, the pattern of results could be described as a positive manifold (cf. Carroll, 1993). The observed positive manifold as well as inspection of the anti-image matrix and Kaiser's (1974) measure of sampling adequacy (MSA > .80) indicated that the correlation matrix was legitimately factorable. In a first step, an exploratory factor analysis (EFA) followed by oblique rotation was performed to obtain first-order factors of intelligence. This analysis resulted in three factors with initial eigenvalues greater than unity (4.84, 1.60, and 1.34, respectively) accounting for 40% of total variance. In the oblique rotation, we allowed the first-order factors to have intercorrelations, ranging from .28 to .36. According to Carroll (1993), interpretation of factors was based on inspection of the highest loadings of each mental test. As can be taken from Table 5, the first first-order factor was characterized by high loadings of all spatial tests (Space 1, Space 2, and Flexibility of Closure) and the four subtests from CFT measuring reasoning abilities by figural material (Series, Classifications, Matrices, and Topologies). The second first-order factor was associated with verbal abilities (Verbal Comprehension and Word Fluency), on the one hand, and with tests showing pronounced speed character (Perceptual Speed and Number 1), on the other. The third first-order factor clearly represented an index of memory, since all memory scales had their highest loading on this factor.

In a second step, factor scores of the first-order factors were subjected to a further EFA. This second-order analysis yielded one single factor with an eigenvalue greater than unity (eigenvalues were 1.85, .60, and .54 for the first, second, and third second-order factor, respectively). This major second-order factor accounted

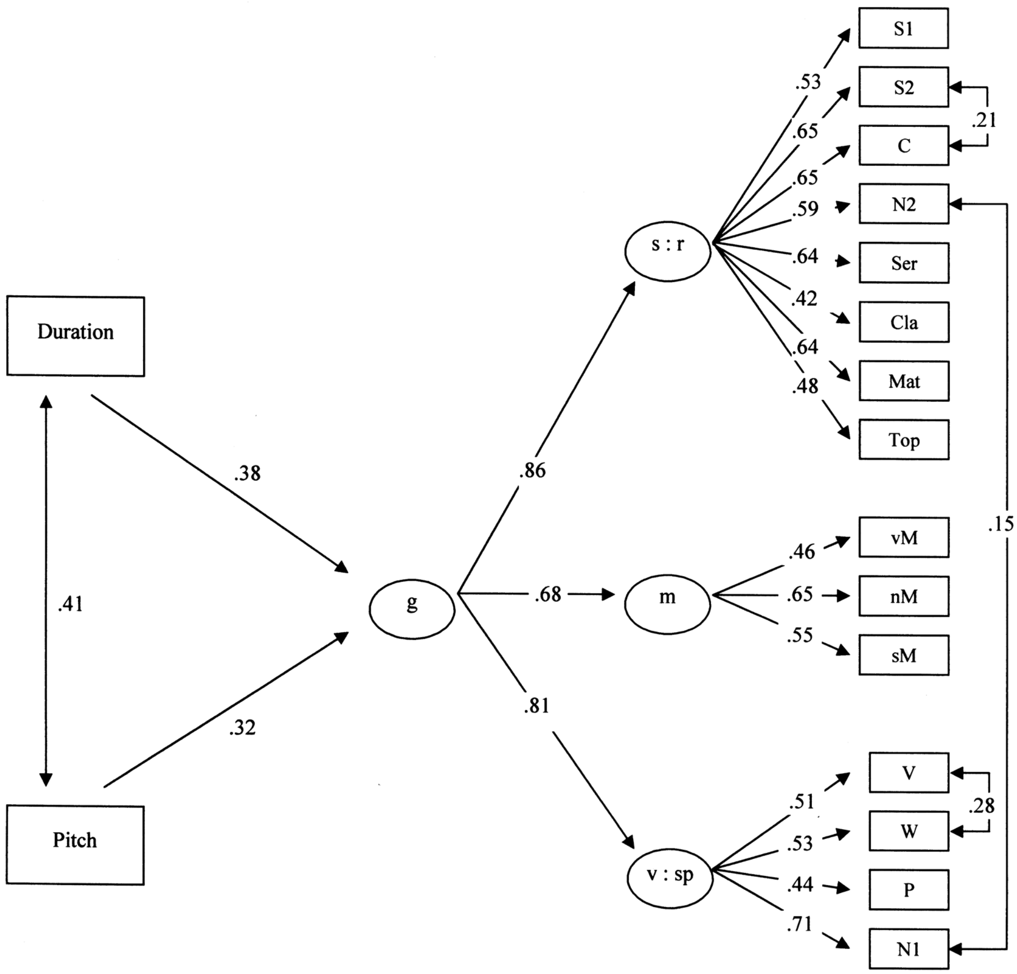

Figure 2. Structural equation model relating temporal discrimination (Duration), pitch discrimination (Pitch), and intelligence with psychometric *g* at the apex of the intelligence hierarchy. First-order factors: s:r = spatial abilities and reasoning; m = memory; v:sp = verbal abilities and speed. For abbreviations of intelligence scales see Table 4.

for 43% of total variance and was characterized by high loadings of each of the lower-order factors (.68, .67, and .61, respectively). According to Jensen (1998; Jensen & Weng, 1994), this kind of highest-order factor emerging at the second-order of a hierarchical factor analysis represents a valid estimate of psychometric *g*.

Correlational analyses yielded statistically significant associations between individual factor scores on psychometric *g* and performances on both discrimination tasks. Correlation coefficients between psychometric *g* and temporal discrimination ($r = .43$, $p < .001$) and psychometric *g* and pitch discrimination ($r = .39$, $p < .001$) were comparable in size. A significant correlation between temporal and pitch discrimination of $r = .41$ ($p < .001$) points to a substantial portion of common variance between both discrimination tasks.

In order to estimate the predicting power of temporal and pitch discrimination and to gain more detailed information about the specificity of the relationship between both psychophysical domains and psychometric intelligence, regression analyses were performed. As single predictors, temporal discrimination and pitch discrimination accounted for statistically significant portions of 18% and 15%, respectively, of the total variance in psychometric *g*. Combination of both predictor variables in a standard multiple regression analysis (cf. Tabachnick & Fidell, 2001) resulted in 24% of explained variance of overall variability in psychometric intelligence. As can be seen from Table 6, both temporal ($t = 4.30$, $p < .001$) and pitch discrimination ($t = 3.51$, $p < .01$) contributed significantly to the prediction of psychometric *g*. Squared semipartial correlations were $sr_i^2 = .09$ for temporal and $sr_i^2 = .06$ for pitch discrimination, indicating that temporal discrimination contributed a considerably higher amount of unique variance to R^2 as compared to pitch discrimination. The remaining 10% of R^2 were attributable to shared sources of variance of both predictor variables. This latter result suggests that temporal and pitch discrimination also contributed a substantial portion of common variance to the prediction of psychometric *g*.

In a final step, a structural model relating individual differences in psychometric intelligence and both sensory domains was constructed using structural equation modeling (SEM) to verify the results obtained by factor, correlational, and regression analyses within a single comprehensive model.

According to the results from hierarchical factor analysis, a hierarchical structure of intelligence with a second-order latent *g* factor of general intellectual capacity and three first-order latent intelligence factors was implemented (see Figure 2). The intersystemic relationships between psychometric intelligence and the two measures of sensory acuity were examined by allowing predictive paths from both temporal and pitch discrimination to psychometric *g*. Correlations between the two verbal subtests (Verbal Comprehension and Word Fluency), the two scales assessing numerical thinking (Number 1 and Number 2), and the subtests measuring spatial ability (Space 2) and Flexibility of Closure were not entirely explained by the first-order factors. Since the shared effects on the specifics of these particular subtests cannot be explained by the respective first-order factors, we allowed for correlated errors of measurement as indicated by the corresponding arrows in Figure 2.

For the model depicted by the path diagram presented in Figure 2, an acceptable degree of fit was observed. This model led to a χ^2 of 143.02 ($df = 112$, $p = .03$), a RMSEA of .04, a CFI of .95, and a TLI of .94. Significant path coefficients of .38 ($t = 5.22$, $p < .001$) and .32 ($t = 4.29$, $p < .001$) for temporal and pitch discrimination, respectively, indicated that the paths from both psychophysical domains to psychometric *g* had substantial predictive strength.

Discussion

Based on an experimental dissociation paradigm, the present study investigated the functional relationship between performance on temporal and pitch discrimination and psychometrically assessed intelligence. In the first instance, this study should provide further empirical evidence for the notion that both temporal and pitch discrimination represent reliable correlates of psychometric *g*. Moreover, the quality of the relationships between temporal and pitch discrimination acuity and psychometric intelligence should be explored more precisely by analyzing unique and shared contributions of temporal and pitch discrimination in predicting psychometric *g*.

Correlational analyses revealed that both temporal ($r = .43$) and pitch discrimination ($r = .39$) were substantially related to psychometric *g*. Furthermore, performance on both tasks showed a considerable amount of common variance ($r = .41$). In regression analyses, temporal and pitch discrimination were found to account for substantial portions of intellectual variance ($R^2 = .18$ for temporal and $R^2 = .15$ for pitch discrimination, respectively). Combination of both predictors in a multiple standard regression analysis of variables resulted in 24% of explained variance in psychometric *g*. Both predictors contributed 10% of shared variance to R^2. The unique contribution of temporal discrimination was considerably higher for temporal ($sr_i^2 = .09$) than for pitch discrimination ($sr_i^2 = .06$). Also, a structure model predicting psychometric *g* by both psychophysical domains yielded acceptable fit indices. For temporal and pitch discrimination, significant path coefficients of .38 and .32, respectively, were observed.

With regard to pitch discrimination, the findings of the present study are in the line with results from earlier studies also investigating the relationship between pitch discrimination and general intelligence. The obtained correlation coefficient of $r = .39$ is consistent with the outcomes of several prior studies reporting correlational relationships in the range of .20 to .50 (e.g., Acton & Schroeder, 2001; Bazana & Stelmack, 2002; Bentley, 1963; Deary, 1994b; Irwin, 1984; Lynn & Gault, 1986; Lynn et al., 1989; Olsson et al., 1998; Raz et al., 1983, 1987, 1990; Watson, 1991). Also, results of regression analysis and SEM indicated that pitch discrimination represents a notable predictor, accounting for 15% of total variance in psychometric *g*. Thus, the findings of the present study yield further evidence for the fact that pitch discrimination can be considered a valid indicator of psychometric intelligence.

An even more meaningful result of the present study, however, represents the fact that also for temporal discrimination, as a rarely investigated correlate of mental capacity, a substantial correlational relationship of $r = .43$ and, correspondingly, considerable power in predicting psychometric *g* could be demonstrated in regression analysis ($R^2 = .18$), and SEM (significant path coefficient of .38). Compared to pitch discrimination, only a small number of studies exists that relate temporal acuity to psychometric intelligence. However, findings from these few investigations consistently conform to the results of the present study. For example, a study of Rammsayer and Brandler (2002) yielded comparable correlations of $r = .35$ and .43 for two measures of duration discrimination in the range of milliseconds and performance on the CFT. Similarly, Watson (1991) reported correlational associations ranging from $r = .17$ to $r = .36$ between three temporal discrimination tasks and scores on the SAT-Math. Most recently, Rammsayer (2005; Rammsayer & Brandler, 2005) showed that a factor analytic compound measure based on eight different temporal tasks accounted for a substantial portion of 31% of overall variability in psychometric *g*.

Thus, the results of the present study corroborate former findings suggesting a functional relationship between psychophysical timing performance and psychometric intelligence. Furthermore, this association seems to be as reliable as the one reported for pitch discrimination as an established psychophysical correlate of psychometric intelligence. When comparing the results obtained for pitch and temporal discrimination in the present study, temporal discrimination appears to be somewhat more closely related to psychometric intelligence than pitch discrimination. The correlational relationship, the predictive power obtained by regression analysis and SEM, and especially the unique contribution derived from standard multiple regression analysis tended to be somewhat more pronounced for temporal than for pitch discrimination. Albeit these differences were far from reaching statistical significance, this finding underlines the validity of temporal discrimination as an alternative indicator of psychometric intelligence.

Results of regression analyses clearly suggested that the relationship between temporal discrimination and psychometric intelligence is not solely due to a general relationship between sensory acuity and intellectual capacity. If so, temporal and pitch discrimination should have accounted for virtually the same portion of variance in psychometric *g* and should not have provided unique contributions to the prediction when combined in a standard multiple regression analysis. Both predictor variables, however, were found to contribute substantial portions of unique variance to the prediction of psychometric *g*. Nevertheless, this analysis also revealed that both predictor variables – in addition to their unique contributions – jointly contributed a substantial portion of shared variance. Thus, with regard to the prediction of psychometric intelligence, our results suggest that temporal discrimination reflects two different sources of intellectual variance. On the one hand, it accounts for a portion of overall variance, which appears to be rather unspecific, as it is shared with pitch discrimination. On the other hand, the finding of a unique portion of variance is consistent with the notion that temporal acuity reflects an essential source of intellectual variance that is probably highly specific to the processing of temporal information.

The finding that temporal and pitch discrimination were related to a common source of intellectual variance points to the conclusion that temporal discrimination partly reflects a rather general aspect of sensory acuity also tapped by other sensory tasks such as pitch discrimination. This finding supports Spearman's (1904) classical notion of some kind of general sensory discrimination ability. According to this hypothesis, general sensory discrimination is supposed to be revealed by the portion of common variance between several sensory discrimination tasks and should be closely related to intelligence (Spearman, 1904). The observed substantial correlation of $r = .41$ between temporal and pitch discrimination provides additional indirect evidence for this view.

Most recent attempts to explain the relationship between sensory sensitivity and psychometric intelligence propose that sensory and cognitive capacity are both determined by underlying biological processes that regulate the fidelity of neural information processing (cf. Li et al., 1998). This view, referred to as *common-cause hypothesis,* is reminiscent of Spearman's supposition that general intelligence and sensory discrimination are not linked directly but based on a more fundamental cause (Deary et al., 2004). Different biological phenomena have been introduced as candidates for a biological basis of the association between general sensory acuity and intelligence such as speed and accuracy of signal transmission (cf. Lynn et al., 1989; Raz et al., 1983) or quality of sensory resolution based on differences in the "hardware redundancy" of the CNS (Raz et al., 1987).

The fact that both temporal and pitch discrimination made substantial unique contributions to the prediction of psychometric intelligence suggests that both tasks – beside common aspects of sensory acuity – also reflect specific intelligence-related facets of discrimination performance not shared by the respective other psychophysical domain. Converging indirect evidence for the existence of such domain-specific aspects in temporal and pitch discrimination tasks has been provided by Kidd, Watson, and Gygi (2000). These authors reported that, as a result of a principal components analysis on different discrimination tasks, duration and pitch discrimination performances showed high loadings on separate factors. Similarly, Watson (1992) found that reading-disabled college students performed significantly more poorly on an auditory temporal task but performed as well as normal controls on pitch and loudness discrimination tasks. Also, this finding is in line with the idea of unique contributions of both psychophysical domains to the prediction of psychometric intelligence.

With regard to temporal discrimination, the existence of unique variance is consistent with the notion that temporal acuity – in addition to more general nontemporal aspects of sensory discrimination – also reflects further specific aspects of neural information processing related to intellectual capacity. Rammsayer and Brandler (2002, 2005) have introduced the temporal resolution power hypothesis as an alternative metaphor to the explanation of the biological basis of psychometric intelligence and its association to speed and efficiency of information processing. Against the background of the results of the present study, Rammsayer and Brandler's (2002, 2005) view of temporal acuity as a possible indicator of temporal resolution power of the CNS obtains further support.

In summary then, the present study provided converging evidence for a functional relationship between psychometric intelligence and accuracy on both temporal and pitch discrimination. Findings suggest that with regard to established sensory correlates of mental capacity, such as pitch discrimination, temporal discrimination can be assigned the status of an equivalent predictor of psychometric intelligence. Furthermore, temporal and pitch discrimination were found to contribute substantial portions of both shared and unique variance to the prediction of psychometric *g*. With regard to temporal discrimination, this finding is consistent with the notion that temporal acuity, in addition to aspects of general sensory discrimination, reflects a specific property of neural functioning associated with general intelligence. Subsequent studies contrasting acuity on temporal discrimination and performance on different sensory discrimination tasks would be highly desirable to further elucidate fundamental mechanisms mediating individual differences in psychometric intelligence.

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