Intelligence 37 (2009) 256–267

Contents lists available at ScienceDirect

Intelligence

Is g an entity? A Japanese twin study using syllogisms and intelligence tests

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ARTICLE INFO

Article history:
Received 1 June 2007
Received in revised form 18 September 2008
Accepted 29 October 2008
Available online 18 December 2008

Keywords:
g
Syllogism
Twin study
Multivariate genetic analysis
Common pathway model
Independent pathway model

ABSTRACT

Using a behavioral genetic approach, we examined the validity of the hypothesis concerning the singularity of human general intelligence, the *g* theory, by analyzing data from two tests: the first consisted of 100 syllogism problems and the second a full-scale intelligence test. The participants were 448 Japanese young adult twins (167 pairs of identical and 53 pairs of fraternal twins). Data were analyzed for their fit to two kinds of multivariate genetic models: a common pathway model, in which a higher-order latent variable, *g*, was postulated as an entity; and an independent pathway model, in which the higher-order latent variable was not posited. These analyses revealed that the common pathway model which included additive genetic and nonshared environmental factors best accounted for the three distinct mental abilities: syllogistic logical deductive reasoning, verbal, and spatial. Both the substantial *g*-loading for syllogism-solving, historically recognized as the symbol of human intelligence, and the emergence of *g* as an entity at an etiological level, that is, at the genetic and environmental factor level, provide further support for the *g* theory.

1. Introduction

There have been lengthy debates over the structure of intelligence. One of the central issues concerns its unitary nature, that is, the singularity of general intelligence versus the multiplicity of different intelligences specific to each of the diverse mental abilities of human beings.

Historically, Spearman (1904, 1927), with his technique of factor analysis, discerned the number of separate underlying factors that account for the observed intercorrelations among multiple abilities. He claimed that individuals' intellectual performance in various intelligence tests is mainly determined by two types of influences: the pervasive general factor (*g*), and a factor specific to each test. On the basis of this two-factor theory, Spearman reasoned that two tests, both heavily loaded with *g*, should correlate more strongly than those less heavily loaded with *g*. In response to Spearman's argument, Thomson (1916) contended that Spearman's hierarchical correlation matrices could be formed without the existence of a general factor, but rather with group factors. Similarly, Thurstone (1938, 1947) introduced a multiple intelligence theory with several broad group factors. However, he later acknowledged moderate intercorrelations among his primary factors, and admitted the possible existence of Spearman's general factor at the second order of analysis. Thus the differences between Spearman and Thurstone were largely a matter of emphasis (Brody & Brody, 1976), that is, the relative significance recognized for the primary and second-order factors. Compromises between these two viewpoints have

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0160-2896/$ – see front matter
doi:10.1016/j.intell.2008.10.010

been proposed, including Vernon's (1950) hierarchical group factor theory, and the Gf (fluid intelligence)–Gc (crystallized intelligence) model of Cattell (1971) and Horn (1989), as well as a Gustafsson's (1988) model with the third-order *g* factor at the top, underlying Gf–Gc–Gv (visualization capacity).

Overall, the models presented thus far all assume a psychometric model postulating an organization of abilities in which some abilities are more general than others. Accordingly, any differences in the number of factors recognized by the model largely depend on empirical results available when each model was formulated, as well as the factorial methods used, or favored, by the researcher (Carroll, 1993).

In stark contrast to the notion of a single, generalized intelligence, the model proposed by Guilford (1967) had a total of 120 (later expanded to 150) factors that are arranged across three dimensions (Guilford, 1985). More recently, Gardner (1983, 1993) introduced Multiple Intelligences theory, in which he argued for the existence of eight relatively independent intelligences. Sternberg (1985) also took a wider view of the nature of intelligence in his “triarchic” theory of intelligence, claiming that intelligence should be understood in terms of adaptation to the real-world environment. Such an enlarged conception of intelligence that seeks to go “beyond IQ” (Sternberg, 1985), as proposed by Gardner and Sternberg, is comprehensive and persuasive. This leads educators, as well as psychologists, to consider intelligence in a broader sense, and to expand their concept of intelligence beyond that which is measured by traditional intelligence tests (Carroll, 1993). These theories also have the appeal of fitting more closely with popular beliefs about intelligence. Thus, although it is widely accepted that the *g* factor is the core of intelligence (Carroll, 1993), and psychometric investigation of cognitive tasks has provided robust and consistent results for a hierarchically structured model with the *g* factor at the top (Gottfredson, 2002), the issue of the structure of intelligence remains controversial.

In contrast to the debate-filled background of psychological research on intelligence, particularly in the field of traditional logic and philosophy, one ability that has been long thought to comprehensively assess human intelligence is logical deductive reasoning. This can be measured by schematic logical inferences, a typical example of which is syllogism-solving (Bochenski, 1970). Syllogisms are a form of logical deductive argument, relating three terms that consist of two premises and a conclusion. Speaking and thinking in a logical fashion has long been considered evidence of intelligence, as was first described by Aristotle in Prior Analytics, 350 B.C. In particular, the deductive reasoning ability expressed in syllogisms was thought to be the symbol of human intelligence. In the Middle Ages, scholastic philosophers analyzed its nature and believed that memorizing a wide variety of patterns of syllogism-solving was a means of cultivating intelligence.

However, little is known about the processes involved in solving syllogisms; studies of cognitive processes of logical deductive reasoning only started in the late 1970s. There are two main theoretical streams in the field of cognitive psychology of logical deductive reasoning. These are “Formal Rule Theory”, in which deductive reasoning processes are based on a syntactic application of the logical structure (Braine & O'Brien, 1998; Rips, 1994), and “Mental Model Theory”, in which deductive reasoning performance depends partly on spatial representations and manipulations of terms of propositions (Johnson-Laird & Byrne, 1991). If both theories are compatible (Grialou & Okada, 2005), then a common ability underlying both strategies can be postulated.

With regard to the association between syllogisms and intelligence tests, a study by Bickersteth and Das (1981) revealed that performance on a syllogism-solving test was higher for children with a high score in the Raven Progressive Matrix than for children with a low score, irrespective of culture. Shikishima, Ando, Grialou, Takemura, and Okada (2005) revealed positive phenotypic intercorrelations among verbal and spatial intelligence subtests, and abstract and graphical (abstract syllogism with graphical aid) syllogism-solving tests. In addition, Ando et al. (2006) reported that the score for each intelligence subtest had substantial positive correlations with the scores for syllogism-solving tests irrespective of the format or type of syllogisms. Stanovich and West (1998) also reported moderate correlations between performance on syllogism-solving and the Scholastic Achievement Test in undergraduate students ($r = .47$ in Exp. 1 and $r = .41$ in Exp. 2). These findings imply that logical deductive reasoning ability, as measured by syllogism-solving, is substantially loaded with general ability, *g*.

In the present study, one of our focuses was to test the validity of the ancient hypothesis that syllogisms are a benchmark of human intelligence. If syllogism-solving can successfully tap human intelligence in general, logical deductive reasoning ability, as measured by syllogisms, will show commonality with mental abilities measured by intelligence tests (e.g., verbal and spatial abilities), which would further confirm the robustness of the emergence of *g*. Therefore, a substantial loading on *g* for syllogistic reasoning ability can be predicted as a more “general” ability than verbal and spatial abilities.

It should also be noted, however, that characterizing the structure of mental mechanisms merely at the phenotypic level is not sufficient. The phenotypic structure provides us with little information about its etiology. In other words, irrespective of the level of correlation among a set of phenotypes, the origins responsible for the overlap are unknown. Multivariate genetic analysis using behavioral genetic models enables us to examine the extent to which genetic and environmental factors mediate the phenotypic covariance between variables, rather than the variance of each variable considered on its own. A growing body of behavioral genetic research has confirmed that the overlap across diverse mental abilities is largely a result of genetic factors (e.g., Alarcon, Plomin, & Fulker, 1999; Cardon, Fulker, DeFries, & Plomin, 1992; Finkel, Pedersen, McGue, & McClearn, 1995; Johnson et al., 2007; Kovas, Harlaar, Petrill, & Plomin, 2005; Luo, Petrill, & Thompson, 1994; Pedersen, Plomin, & McClearn, 1994; Plomin, Pedersen, Lichtenstein, & McClearn, 1993; Rijsdijk, Vernon, & Boomsma, 2002). Such findings have been obtained not only within different psychometric tests of cognitive abilities, but also within more basic information-processing measures and psychophysical measures of basic cognitive processes such as working memory, reaction time, and inspection time, as well as between psychometric tests and basic cognitive measures (Ando, Ono, & Wright, 2001; Baker, Vernon, & Ho, 1991; Friedman et al., 2008; Luciano Smith et al., 2001; Luciano Wright et al., 2001; Neubauer, Spinath, Riemann, Angleitner, & Borkenau, 2000; Petrill, Luo, Thompson, & Detterman, 1996; Polderman et al., 2006; Posthuma, De Geus, & Boomsma, 2001; Posthuma et al., 2002; Rijsdijk, Vernon, & Boomsma, 1998).

Even so, in light of the unitary concept of *g*, modeling human intelligence in terms of genetic overlap, as expressed by genetic correlations across cognitive abilities alone, is still insufficient. Although a high genetic correlation among several abilities could imply the existence of a dominating common factor, to which the genetic factors contribute, this might equally reflect a mere aggregation of independent abilities that are attributable to genetically overlapping, but different, origins. To be more precise, environmentally different sources for each ability, irrespective of the strength of the genetic correlation, may indicate the independence of each ability, which are not subdominant to a common entity. To confirm the *g* theory (the singularity of human intelligence) from a behavioral genetics perspective, it is necessary to model the organization of intelligence with a higher-order construct, *g* as an entity, at the genetic and environmental factor level, and to empirically show that the model with a higher-order construct better explains the data than the model without a higher-order construct.

A simplified example of this approach is shown in Fig. 1, where only the overlapping components of three distinct, but coexisting, physical symptoms, fever, sore throat, and muscle pains, are illustrated with two different models, namely, a simplified independent pathway model and a simplified common pathway model. Here, for the sake of clarity, factors specific to each symptom are omitted. In the independent pathway model (i.e., the biometric model; McArdle & Goldsmith, 1990), the covariance of the three symptoms is accounted for by the overlapping genetic and environmental factors, to varying degrees, and these factors directly influence each symptom. This model does not require the presence of a higher-order variable to which all symptoms must be related. As such, it is assumed that one could have some symptoms but not necessarily others. On the other hand, in the common pathway model (i.e., the psychometric model; Kendler, Heath, Martin, & Eaves, 1987), each symptom is described as subdominant to a higher-order latent construct that can be recognized as a real entity, and thus labeled "influenza". As such, it can be assumed that, regardless of whether the cause is genetic or environmental, one is infected not with each specific symptom, i.e., fever, sore throat, and muscle pains, but rather the higher-order entity *per se*, namely, influenza (see Jang, 2005 for details of independent pathway and common pathway models). Using these two different models to approach co-occurrence of symptoms is particularly useful in classifying diagnoses of complex mental disorders on the basis of the genetic and environmental structure of comorbid symptoms (Jang, 2005). To determine which of these two etiological possibilities better explains the organization of comorbidities, Jang emphasized the effectiveness of fitting the two alternative models. On that basis, he proposed that the current diagnostic framework of mental disorders should be revised to better reflect their underlying structures.

The same can be applied to the case of *g*. If *g* exists not only phenotypically but also etiologically as a higher-order construct underlying cognitive abilities, the common pathway model should explain each ability better than the independent pathway model. The common pathway model implies that genetic and environmental effects contribute to a psychological entity, *g*, *per se*, rather than directly to each ability, and that each ability is subdominant to *g*. Alternatively, if *g* is not an entity but merely an artifact, the model that does not include the latent factor should exhibit a better goodness-of-fit. The independent pathway model would suggest that *g* does not exist as an entity, but rather that the overlap can be accounted for by pleiotropic effects and/or by the common influence of environmental factors on sets of individual abilities.

In most of the earlier studies that attempt to clarify the structure of intelligence, the common pathway model has not been applied, or, when it has been applied, was not compared with the independent pathway model (Finkel et al., 1995; Petrill, 2002; Petrill, Saudino, Wilkerson, & Plomin, 2001; Petrill et al., 1998; Plomin & Spinath, 2002; Rijsdijk et al., 2002). A comparison of these two models was carried out using IQ, reading ability, inattention, and impulsivity (Zumberge, Baker, & Manis, 2007), but IQ itself represents general intelligence, and its association with personality traits does

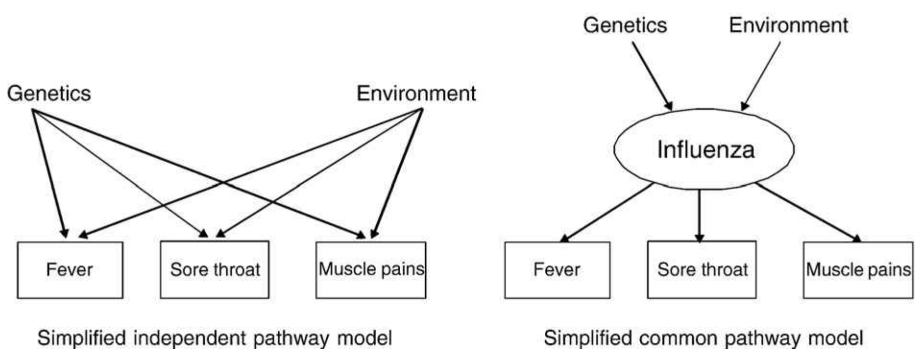


Fig. 1. The two models: without a higher-order latent factor (Simplified independent pathway model) and with a higher-order latent factor (Simplified common pathway model).

not explain the structure of intelligence. To substantiate the *g* theory from a behavioral genetics perspective, organization of intelligence needs to be modeled with a higher-order construct postulated underlying each ability in a best-fitting model. The existence of a unitary structure of human intelligence not only at a phenotypic level but also at an etiological level, that is, a unitary, genetic and environmental factor level, would provide further evidence for the *g* hypothesis, when these factors act across human intelligence.

Given the background mentioned thus far, we propose the following two hypotheses. First, the ability that has historically been referred to as the symbol of human intelligence, namely, syllogistic deductive reasoning ability, will be strongly *g*-loaded. Second, general intelligence *g* will be identified not only at a phenotypic level but also at its genetic and environmental factor level. If this is the case, the multivariate genetic model with a higher-order construct will explain the empirical data better than the multivariate genetic model without a higher-order construct.

To test these hypotheses, we used a syllogism-solving test that included a variety of formats and types, and a full-scale intelligence test as a battery of tests to encompass diverse abilities with a high level of reliability. We used a multivariate behavioral genetic approach with analyses based on structural equation modeling for logical deductive reasoning ability, as measured by syllogisms, and cognitive abilities, as measured by intelligence tests. Specifically, we constructed two kinds of alternative models: (a) the independent pathway model, a multivariate genetic model without a latent factor, and (b) the common pathway model, a multivariate genetic model with the latent factor *g* as a higher-order construct. The two distinct models were compared in terms of goodness-of-fit. From the standpoint of behavioral genetics, we considered that this study would provide further evidence for the *g* theory when both of these hypotheses are supported.

2. Method

2.1. Participants

The Keio Twin Project (KTP) recruited 14–30 year-old twin participants through population based registries in some parts of the Tokyo area in 1998–2002. Participation in the project was voluntary, and, of 6000 pairs of twins to whom we had sent letters, approximately 1000 pairs of twins agreed to participate in our research (for a detailed description of the KTP, see Shikishima, Ando, Ono, Toda, & Yoshimura, 2006). After recruitment, the registrants were assessed by questionnaires delivered via mail surveys and by cognitive ability tests or physical measurements conducted at Keio University.

In 2005–2006, the KTP called for the registrants to attend a cognitive test session held at Keio University for the present study. A total of 448 twins, including 118 males and 330 females, took part in the study, with a response rate of then active KTP registrants of 26%. The age of the participants ranged from 17 to 36, with a mean of 24.93 and standardized deviation of 4.36. The participants were paid for ¥5000 (approximately 40 US dollars) as a fee for their participation.

Zygosity of all the twin pairs who attended the session was determined by DNA microsatellite analysis, where the concordance of the STR type within the twin pair was examined at a maximum of ten informative loci. DNA was obtained from each participant via a buccal smear, in which cells were taken from the back side of the cheek with a swab. For all the twin pairs diagnosed as monozygotic (MZ), the probability for being an MZ twin pair by means of the Bayesian theorem exceeded 99.2%. The number of each type of twin pairs according to the DNA-based zygosity diagnosis was as follows: 43 identical male (MZm), 124 identical female (MZf), 7 fraternal male (DZm), 31 fraternal female (DZf), and 15 fraternal male–female (DZo) pairs. The DZo pairs were excluded from the genetic analyses, and the analyses were conducted for the same sex pairs.

The participants were informed of the purpose of the study, the research items, protection of their privacy, and their right to cancel their participation at any time, and signed informed consent was obtained for all participants at the beginning of the experimental session.

2.2. Procedures

2.2.1. Test design

The experimental session lasted for approximately two-and-a-half hours, including a break. The session consisted of two parts: a syllogism-solving test and an intelligence test. Identical sessions were repeated 12 times for six days in the same room and by the same testers in groups of less than 60 participants. The room was divided in half, and twin pairs were seated separately with adjacent seats left vacant.

2.2.2. Syllogism-solving test

The Keio BAROCO Project has developed syllogism-solving tests since 2004, known as the BAROCO tests, in an attempt to investigate the logical properties of syllogistic deductive reasoning abilities (Ando et al., 2006; Shikishima et al., 2005). Prior to this study, more than one thousand participants had completed a version of the BAROCO test, which led to the production of a reliable test that successfully measures logical deductive reasoning ability. The most recent version, BAROCO II.3, was used in the current study.

The BAROCO II.3 comprises five different formats, namely, Abstract, Graphical, Content-based (belief-neutral), Belief-congruent, and Belief-incongruent. An example of each format is shown in Appendix A. In the Abstract test, concrete terms are not used, but are replaced by abstract capital letters A, B, and C. In the Graphical test, abstract syllogisms are presented with a graphical representation of two premises. The graphical representation is based on a modified version of Euler circles (Stenning & Oberlander, 1995). For the Content-based, Belief-congruent, and Belief-incongruent tests, the terms are stated in ordinary words, but the conclusion describes a particular situation whose truth is determined by the context. In the case of the Content-based test, the conclusions are independent of our belief systems. By contrast, in the Belief-congruent test, the conclusions were congruent with our belief, that is, true in our real world, whereas in the Belief-incongruent test, the conclusions were incongruent with our belief, or false, in our real world.

Each format included twenty problems, with a total 100 questions. Belief-congruent and Belief-incongruent problems were mixed and divided in two subtests. Participants were required to solve problems consisting of five subtests, one for

Table 1
Description of the Kyodai Nx15- group intelligence test

Subtest	Assessment activity	Time (min.)	*N* of items
Verbal			
Memory	Recalling details of a story that had been read out before the last task.	1	10
Word completion	Identification of a word by filling in a Japanese alphabet character (hiragana).	40 sec	30
Antonym or synonym	Multiple choice identification of a word which has either similar meaning or opposite meaning of a given word.	1	25
Sentence completion	Completion of a sentence by choosing correct words from multiple choices.	1.5	12
Rearrangement of words	Construction of jumbled sentences in the correct sequence and selection of a correct answer which best fits from multiple choices.	2	12
Word matrix	Identification of the most appropriate word from multiple choices to arrange the words in a meaningful order.	1	15
Spatial			
Sociogram	Identification of the relationship between 4 persons when the relationships of the 2 persons are displayed.	2.5	8
Combination of figure and letter plates	Interpretation of a two- dimensional figural rotation by matching two plates with various angles.	3	12
Figure combination	Drawing a line to divide a figure followed by rearranging in order to form a complete square.	2	13
Punching a folded paper	Identification of the pattern of holes that will result when a piece of folded and punched paper represented is unfolded.	1	12
Numerical			
Calculation method	Identification of the calculation method which represents how to calculate in order to give the answer to the verbally presented question.	1.5	12
Index conversion	Identification of the correct equation when the symbol is converted.	1	12

each format. In addition to these variations in each format, four types of figures were included in both the premises and the conclusions. The four figure types were: universal affirmative, universal negative, particular affirmative, and particular negative (Johnson-Laird, 1983). In accordance with Aristotelian syllogism classification, different combinations of these types of figures were used for each of the 20 problems in each format, and the same set appeared five times in different formats, which provided various levels of difficulty in syllogistic deductive reasoning (see Ando et al., 2006 for the detailed description of the BAROCO test). The number of answer alternatives was five, which comprised four possible conclusions and a "no valid conclusion", but a correct answer was never allocated to "no valid conclusion".

At the beginning of the syllogism-solving test, participants were given a three-minute practice session in which they solved ten problems representing the four formats, i.e., Abstract, Content-based, Belief-congruent, and Belief-incongruent. In addition, prior to each six-minute subtest, an exercise problem was given to ensure participants understood differences between the formats.

In this sample, Cronbach's α ranged from .83 to .88 for each subtest, and reached .96 for the total score, which guaranteed a high level of reliability in terms of the internal consistency of the test. Hence, the total score of the five subtests of the BAROCO II.3 test was used as the measure of logical deductive reasoning ability (hereinafter referred to as "Logical").

2.2.3. Intelligence test

For the intelligence test, we used the full version of the Kyodai Nx15- (Lynn, Hampson, & Bingham, 1987; Osaka & Umemoto, 1973), one of the most popular group intelligence tests in Japan. This test was designed for those over the age of 15, and was constructed and standardized by psychologists in the Educational Psychology Department at Kyoto University. There are 12 subtests altogether, which are described in Table 1.

The individual scores of each subtest of the Kyodai Nx15- were converted to standardized *T* scores, with a mean of 50 and standard deviation of 10, by following the score conversion chart attached to the scoring manual. Since a mean IQ score of 101.91 and a standard deviation of 14.07 were gained by applying the mean and the standard deviation of individual total *T* scores of the 12 subtests to the IQ conversion chart, we can assume that our twin sample is broadly representative of the general population in terms of the intelligence test score.

The principle component analysis with promax rotation conducted for all 12 subtests of the Kyodai Nx15-extracted two factors with an eigenvalue of more than 1 (Table 2). It was clear that the first factor represents the verbal factor, and the second factor the spatial factor. We excluded two subtests, Memory and Word matrix, because they were loaded almost equivalently across the two factors. We also excluded two numerical tests to conceptually and empirically clarify the construct of verbal and spatial scores. As a result, the measure of verbal ability comprised the total standardized *T* score for: Word completion, Sentence completion, Antonym or synonym, and Rearrangement of words (referred to as "Verbal"). The measure of spatial ability consisted of the total

Table 2
Principal component analysis for the Kyodai Nx15- subtests (promax rotated)

Subtest	Factor	
	1	2
Word completion	.88	−.35
Sentence completion	.81	.02
Antonym or synonym	.66	.17
Rearrangement of words	.58	.21
Calculation method	.42	.19
Word matrix	.32	.31
Punching a folded paper	−.15	.78
Figure combination	−.13	.77
Combination of figure and letter plates	.07	.70
Sociogram	.12	.49
Index conversion	.22	.45
Memory	.30	.39

Table 3
Descriptive statistics for Logical (syllogism-solving) tests

Test	*N* of items	Min	Max	Mean	S.D.	Age effect [a)]	Sex effect [b)]
Logical (total)	100	4	99	52.90	20.68	−.29 ***	.90
Content-based	20	1	20	8.63	4.28	−.25 ***	.01
Abstract	20	0	20	9.80	4.56	−.21 ***	.09
Graphical	20	0	20	10.65	5.13	−.26 ***	.13 **
Congruent	20	2	20	11.86	4.66	−.26 ***	.05
Incongruent	20	0	20	11.91	5.21	−.25 ***	.05

N=446– 448; ***p*<.01; ****p*<.001.
[a)] presented as Pearson correlation coefficients with age.
[b)] presented as Pearson correlation coefficients with sex when female scores are 0 and male scores are 1.

standardized *T* score for: Punching a folded paper, Figure combination, Combinations of figure and letter plates, and Sociogram (referred to as "Spatial"). Modified examples of each subtest are shown in Appendix B.

2.3. Statistical analyses

2.3.1. Phenotypic analyses

Means, standard deviations, and ranges were calculated for the total score and for each subtest of Logical, Verbal, and Spatial. The age and sex effects were also examined. Pearson correlations were analyzed among subtest scores and among total scores of Logical, Verbal, and Spatial to characterize phenotypic associations among them. SPSS 14.0 was used for these analyses.

2.3.2. Twin intraclass correlation analyses

For the subtest and total scores for Logical, Verbal, and Spatial, similarities were compared between MZ and same sex DZ twin pairs. MZ twin pairs share the same genes and common family environment, whereas DZ twin pairs share one-half of their genes on average and common family environment. As such, we can assume that the genetic similarity for MZ twin pairs is twice that for DZ twin pairs, while the shared environmental similarity for both types of twin pairs is equal. Therefore, intraclass correlations that are higher for MZ than DZ twin pairs indicate the presence of genetic effects. By contrast, if there is no difference in intraclass correlations between both types of twin pairs, the presence of shared environmental effects without genetic effects is likely.

2.3.3. Multivariate genetic analyses

To clarify the genetic and environmental overlap of Logical, Verbal, and Spatial, multivariate genetic models were fitted to the twins' variance–covariance matrices with structural equation modeling using the maximum likelihood method (for more details see Neale & Maes, 2002). The multivariate genetic analysis decomposes the twins' observed (phenotypic) variance and covariance into components attributable to additive genetic (A), dominance genetic (D), shared environmental (C), and nonshared environmental (E) influences. Additive genetic influences reflect variation in multiple genotypes whose influences are small but are additive to form a quantitative phenotype. Dominance genetic influences represent variation in interactions between alleles at the same locus. Shared environmental influences refer to the variation in environmental characteristics that make family members alike and that differ between families. By contrast, nonshared environmental influences reflect the variation in environmental characteristics that make family members different, even if they live together. All of the measurement error components are also included in the nonshared environmental effect. We assumed that all of these effects are independent.

We began the model-fitting analysis by fitting a saturated model in which the means, variances and covariances of each zygosity group for the Logical, Verbal, and Spatial scores were estimated. Then, a series of full models (ADE and ACE models) and sub-models (AE and CE models) for the independent pathway model and the common pathway model was fitted to the raw Logical, Verbal, and Spatial scores. The indices of model fit were compared to identify the model that best accounted for all three variables. The contribution of each parameter to the best-fitting model was estimated as a standardized path coefficient.

To evaluate the comparative fit of competing models, differences in values in Akaike's information criterion (AIC; Akaike, 1987) and the Bayesian information criterion (BIC; Schwarz, 1978) from a saturated model were reported. For both the AIC and BIC values, better-fitting models have smaller values. Chi-squared significance tests with the saturated model were also applied. The Mx software package was used for genetic analyses (Neale, 2004).

3. Results

3.1. Phenotypic analyses

Table 3 shows the descriptive statistics for Logical (the syllogism-solving test). The mean score for each subtest increased as the test period progressed, and the *t*-test indicated that the mean differences between a subtest and the next subtest were significant (Content-based and Abstract, $t(445)=-6.22$, $p<.0001$; Abstract and Graphical, $t(445)=-4.55$, $p<.0001$; Graphical and Congruent, $t(445)=-7.50$, $p<.0001$; Congruent and Incongruent, $t(447)=-.43$, *ns*, they were mixed together). The mean and standard deviation for eight subtests and total scores for Verbal and Spatial are presented in Table 4. Fig. 2 illustrates the distributions of each total score for Logical, Verbal, and Spatial.

Table 4
Descriptive statistics for Verbal and Spatial tests

Test	Mean	S.D.	Age effect [a)]	Sex effect [b)]
Verbal (total)	208.11	32.80	−.08	.04
Word completion	52.39	9.47	−.01	−.05
Sentence completion	51.50	9.95	−.08	−.03
Antonym or synonym	52.33	12.14	−.06	.12 *
Rearrangement of words	51.90	11.43	−.08	.04
Spatial (total)	204.32	30.12	−.13 **	.13 **
Punching a folded paper	48.17	10.74	−.06	.09
Figure combination	51.19	10.89	−.10 *	.16 **
Combination of figure and letter plates	52.58	11.21	−.09 *	.06
Sociogram	52.39	9.40	−.10 *	.07

N=448; **p*<.05; ***p*<.01.
[a)] presented as Pearson correlation coefficients with age.
[b)] presented as Pearson correlation coefficients with sex when female scores are 0 and male scores are 1.

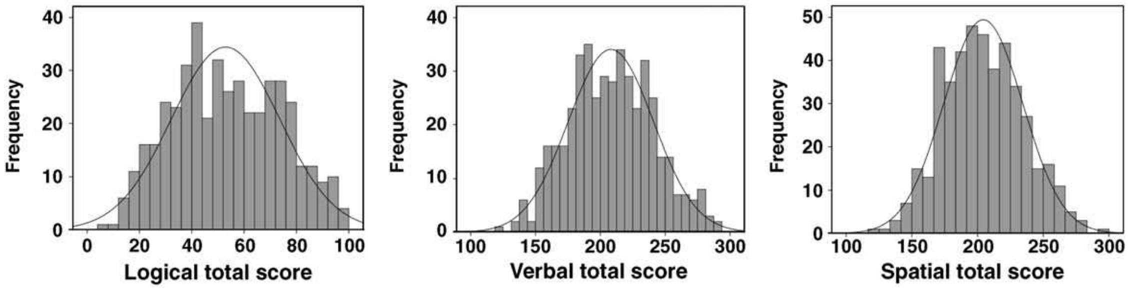


Fig. 2. Distributions of Logical, Verbal, and Spatial raw scores.

No significant mean differences were observed for any measures between zygosities or between first-born and second-born twins. However, we observed significant age effects for all of the Logical subtests (Table 3) and for some of the Verbal and Spatial subtests (Table 4). Minimal but significant sex effects were also observed for some subtests. Therefore, we used adjusted scores that were controlled for age and sex effects in subsequent analyses.

Intercorrelations among the subtests of Logical, Verbal and Spatial are shown in Table 5. High correlations were observed within the Logical subtests ($r = .58–.84$), and relatively higher correlations were found between some of the Logical and Verbal subtests (e.g., $r = .46$ between Content-based/Incongruent and Sentence completion). Moderate correlations were shown between each subtest of Logical and Spatial ($r = .22–.36$).

Intercorrelations among Logical, Verbal, and Spatial were also high and ranged .48–.54 (Table 6). These correlation coefficients were very similar, implying that these three distinctive abilities could share a common construct to the same degree.

3.2. Twin intraclass correlation analyses

Intraclass correlations for MZ twin pairs were high for all subtests ($r = .39–.63$), whereas those for DZ twin pairs were relatively lower ($r = .15–.60$) (Table 7). With the exception of the first administered Logical subtest (Content-based) and two Verbal subtests (Sentence completion and Antonym or synonym), large differences between MZ and DZ intraclass correlations were observed, which indicate substantial genetic influences for each subtest.

For the total scores of Logical, Verbal, and Spatial, MZ intraclass correlations were very high and close in value ($r = .67–.73$). By contrast, DZ intraclass correlations were low for Logical and Spatial ($r = .28$), but high for Verbal ($r = .62$).

3.3. Multivariate genetic analyses

The results of the model-fitting analysis are shown in Table 8. The AE common pathway model showed the best fit for all of the fitting indices. For all models other than the AE independent pathway model, differences in BIC values with the AE common pathway model approached or exceeded 10, which is defined as "strong" or "very strong" evidence in favor of the model with a smaller BIC value in terms of posterior odds (Raftery, 1995). As for the AE independent pathway model, the difference in BIC value with the AE common pathway model was 5, which still provided "positive" evidence that the model with a smaller BIC value (the AE common pathway model) fitted better than the other model (the AE independent pathway model). The smallest AIC value for the AE common pathway model (-42.20) further indicated the predominance of this model over the other competing models.

Fig. 3 depicts the standardized path diagram when the three variables were incorporated into the best-fitting model (the AE common pathway model). The three abilities were equally influenced by a common latent construct, with a factor loading of .73 (95% CI: .64–.81) for Logical, .72 (95% CI: .62–.80) for Verbal, and .69 (95% CI: .60–.77) for Spatial, which means that the relative contributions of the common construct and of specific factors were broadly equivalent for the three abilities. The common latent construct was revealed to be highly heritable, with a heritability of 83% (95% CI: 74–88%). Each ability was also affected by specific genetic factors with a heritability of 22% (95% CI: 11–34%) for Logical, 30% (95% CI: 20–42%) for Verbal, and 31% (95% CI: 20–42%) for Spatial.

4. Discussion

Our twin data provided evidence that *g* exists not as a mere overlap of distinct human mental abilities, but as an entity at the genetic and environmental factor level. The two hypotheses we proposed as evidence for the existence of *g* at the etiological level were both supported in the present study. Syllogism-solving and other specific abilities, as measured by intelligence tests, were substantially *g*-loaded, and the three distinct abilities (logical deductive reasoning, verbal, and spatial abilities) were best explained with a general construct at the top, and each particular ability subordinate to the higher construct. The better goodness-of-fit for the common pathway model (in which a higher-order construct is hypothesized as an entity) compared with the independent pathway model (in which commonalities are not postulated as an entity) lends plausibility for the existence of *g* in terms of its genetic and environmental origin. Therefore, the singularity of human intelligence described in the *g* theory, which Spearman (1904) put forth with his method of factor analysis some 100 years ago, was born out by research using modern statistical methodology in behavioral genetics, i.e., multivariate genetic analysis with structural equation modeling.

Accordingly, our findings could furnish an argument against the typical criticisms offered by those who are opposed to the

Table 5
Intercorrelations among subtest scores for Logical, Verbal, and Spatial

	Content-based	Abstract	Graphical	Congruent	Incongruent	Word completion	Sentence completion	Antonym or synonym	Rearrangement of words	Punching a folded paper	Figure combination	Combination of plates	Sociogram
Content-based	1.00												
Abstract	**.58**	1.00											
Graphical	**.59**	**.65**	1.00										
Congruent	**.63**	**.68**	**.74**	1.00									
Incongruent	**.61**	**.65**	**.69**	**.84**	1.00								
Word completion	.19	.15	.16	.18	.18	1.00							
Sentence completion	**.46**	.36	.39	**.43**	**.46**	**.45**	1.00						
Antonym or synonym	**.42**	.37	**.40**	.38	**.44**	.36	**.60**	1.00					
Rearrangement of words	**.43**	.33	.38	.37	**.40**	.32	**.49**	**.42**	1.00				
Punching a folded paper	.27	.25	.31	.27	.29	.09	.27	.27	.31	1.00			
Figure combination	.25	.30	.35	.33	.29	.14	.25	.28	.22	**.42**	1.00		
Combination of figure and letter plates	.34	.27	.36	.34	.36	.15	.35	.38	.38	**.41**	.35	1.00	
Sociogram	.31	.22	.33	.31	.30	.12	.28	.29	.32	.19	.23	.38	1.00

All the correlations except that between Word completion and Punching a folded paper are significant ($p<.05$).
Correlation coefficients above .40 are shown in boldface.

concept of *g*; in other words, *g* is an “artifact” (Simon, 1969) of the statistical methods that psychologists apply to the data. Gould (1981) argued that *g*, as a factor extracted from the factor analysis, is neither a “thing with physical reality” nor a “causal entity”, but is a “mathematical abstraction”, maintaining that “we cannot reify *g* as a ‘thing’ unless we have convincing, independent information beyond the fact of correlation itself.” Although the present study also draws information from correlations, we were able to depict the structure of human intelligence beyond the fact of phenotypic and genetic correlations with an explicit comparison between the independent pathway and the common pathway model; and as a “causal entity”, as a highly genetically driven entity.

Logical deductive reasoning ability as measured by syllogism-solving was highly *g*-loaded. It is noteworthy that a “homogeneous” ability such as solving syllogisms was comparable to “heterogeneous” abilities such as spatial and verbal tasks in the intelligence test, jointly constituting *g* with equally high loading. Pervasive correlations between BAROCO subtests and intelligence subtests, irrespective of whether syllogism-solving was aided by graphical representations or not, or whether the task in the intelligence subtest was verbally or spatially posed, suggest that syllogism-solving is not reduced to a particular ability, but should be considered as a comprehensive general ability that integrates several aspects of human intelligence. Our data strongly suggest that syllogisms, which have symbolized human intelligence in philosophy since Aristotle, characterize one of the best markers of *g* from psychological and behavioral genetic points of view.

However, this does not necessarily mean that the syllogistic deductive reasoning ability measured in the present study characterizes the essential nature of *g*. It is misleading to describe the nature of *g* by referring to the property of high *g*-loading tasks. Syllogisms are a “vehicle” of *g*, if we quote from Jensen (1998). As he mentioned, “The vehicle is not the construct; the construct is not the vehicle.” By the same reasoning, the singularity of human intelligence, which was shown empirically by our data, does not necessarily indicate a single process of human intellectual activity. Despite its unitary organization, the processes by which the *g* factor affects human mental abilities may well be complex. The present study and others (e.g., Plomin & Spinath, 2002) revealed that *g* is genetic and pervasive, and affects a variety of operations ranging from elemental cognitive tasks to intellectually complex psychometric tasks in the brain and in the mind; however, the essential nature of *g* or the features of the “passengers” in the vehicle remains unknown.

Our data identified *g* to be extremely heritable, with a heritability of 83% (95% CI: 74–88%). Similar heritability estimates have been previously reported in some studies that analyzed test scores of spatial, verbal, memory, and speed of

Table 6
Intercorrelations among Logical, Verbal, and Spatial scores

	Logical	Verbal	Spatial
Logical	1.00		
Verbal	.54	1.00	
Spatial	.50	.48	1.00

All the correlations are significant ($p<.001$).

Table 7
Twin intraclass correlations

	rMZ	rDZ
Logical (total)	.67	.28
Content-based	.46	.39
Abstract	.41	.20
Graphical	.59	.15
Congruent	.54	.16
Incongruent	.56	.26
Verbal (total)	.73	.62
Word completion	.48	.20
Sentence completion	.63	.58
Antonym or synonym	.55	.60
Rearrangement of words	.46	.18
Spatial (total)	.69	.28
Punching a folded paper	.47	.31
Figure combination	.52	.18
Combination of figure and letter plates	.53	.29
Sociogram	.39	.21

DZ opposite-sex pairs were excluded from analyses.

processing abilities (81–82%) (Finkel et al., 1995; Pedersen et al., 1994; Plomin et al., 1993), or verbal, perceptual, and image rotation abilities (77% CI: 66–84%) (Johnson et al., 2007). However, our heritability estimate is generally higher than those from earlier studies, which were approximately 50% (Plomin, DeFries, Craig, & McGuffin, 2002). This might be a result of the fact that our tests included syllogisms. The increase in means and genetic effects with repetition of the syllogism-solving subtests indicates that Logical could include the participants' ability to learn. However, the result of multivariate genetic analysis did not change when Logical was replaced by the first syllogism-solving subtest score or the last syllogism-solving subtest score. Therefore, the concern that the results of the present study can be attributed to the fact that Logical reflects learning ability can be ruled out. The extremely high heritability of psychometric *g* estimated in the present study, almost beyond the range of heritability typically observed in human psychological traits, can be explained as a result of including a good marker of *g*, namely, syllogisms.

Several recent reports have shown that *g* is also correlated with a variety of neural mechanisms, such as glucose metabolism (Haier, 2003), cortical development (Shaw et al., 2006), and biochemical activity (Jung et al., 2005), along with the identification of promising endophenotypes for intelligence such as working memory and processing speed (van Leeuwen, van den Berg, Hoekstra, & Boomsma, 2007). These studies allow us to assume that it is now reasonable to consider *g* to be a physiological or biological, genetic entity. It would be intriguing to investigate the extent to which the logical deductive reasoning ability, as measured by syllogisms, is correlated with these physiological measures.

Finally, as a limitation of the present study, it should be noted that, with this relatively small sample size, the power might not be sufficient to detect the effects of shared environment (C) and/or dominance genetics (D). Subsequent power analyses revealed that, to reject the AE common pathway model with 80% power (at the .05 significance level) in favor of the ACE common pathway model and the ADE common pathway model, we would require respective sample sizes of approximately 988 and 2368 twin pairs (given the current proportion of MZ and DZ pairs).

Another important limitation is that it is unclear whether the data used here, where only three kinds of abilities (the minimum number needed for factor analysis) were measured by paper-and-pencil psychometric tests and analyzed, are representative of diverse human intelligence abilities. Thus, we cannot rule out the possibility that the latent factor extracted in this study might appear as a common factor besides *g* in different tests. In other words, this latent factor might not necessarily be *g*, but might emerge as a group factor, when another wider range of abilities are incorporated into the analysis. At the same time, there remains the possibility that we failed to extract genetic components shared by only two of the three abilities but not by the remaining ability. These components are not necessarily independent, even though they were included in our multivariate model as residual variance in the specific genetic components. They might appear as genetics of *g* when we include another type of mental ability in the analysis. If this is the case, we might see even larger effects of *g* on an analysis covering a wider range of abilities. Further studies that include more diverse abilities are needed to confirm these findings.

Nevertheless, our results support the existence of *g* as an entity from an etiological perspective based on the ancient symbol of human intelligence.

Acknowledgments

We wish to thank Akiko Hirao and Kaoru Kaneshiro for conducting the twin zygosity diagnoses using the DNA microsatellite method at the Toda laboratory of Osaka University. We would also like to express our gratitude to the twins registered with the Keio Twin Project, who participated in this study. This study is supported in part by

Table 8
Model-fitting indices for multivariate analyses

Model	−2LL	*df*	*N* of pa	Δ AIC	Δ BIC	$\Delta\chi^2$	Δ*df*	*p*
Saturated	11,010.97	1183	54					
ADE independent pathway	11,050.31	1216	21	−26.66	−68.40	39.34	33	.21
ACE independent pathway	11,049.05	1216	21	−27.92	−69.03	38.08	33	.25
AE independent pathway	11,050.31	1222	15	−38.66	−84.41	39.34	39	.46
CE independent pathway	11,073.32	1222	15	−15.65	−72.91	62.35	39	.01
ADE common pathway	11,048.58	1220	18	−36.39	−79.94	37.61	37	.44
ACE common pathway	11,049.08	1220	18	−35.89	−79.69	38.11	37	.42
AE common pathway	**11,050.77**	**1224**	**14**	**−42.20**	**−89.52**	**39.80**	**41**	**.52**
CE common pathway	11,136.25	1224	14	43.27	−46.78	125.27	41	<.0001

The best-fitting model is shown in boldface.

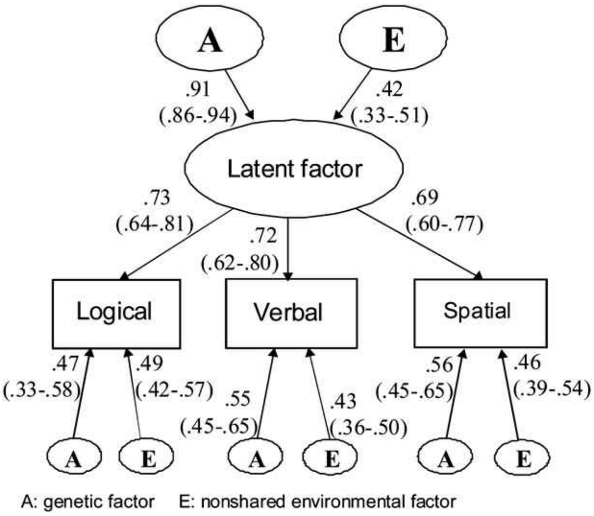


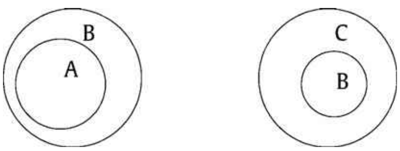
Fig. 3. Standardized path diagram depicting the best-fitting model for logical deductive reasoning, verbal, and spatial abilities. 95% confidence interval estimates are noted in brackets.

grants from the Interdisciplinary Graduate Program on the Mind, Brain and Reasoning, Keio University.

Appendix A. Examples of syllogism-solving tasks according to formats

Abstract:
All A are B. All B are C.
(1) All A are C. (2) Some A are not C. (3) All C are A. (4) Some C are not A. (5) No valid conclusion.

Graphical:
All A are B. All B are C.



(1) All A are C. (2) Some A are not C. (3) All C are A. (4) Some C are not A. (5) No valid conclusion.

Content-based (belief-neutral):
No one in this village is Mary's friend. All Tom's friends are Mary's friends.
(1) All Tom's friends live in this village. (2) Some of Tom's friends live in this village.
(3) Some of Tom's friends do not live in this village. (4) None of Tom's friends live in this village. (5) No valid conclusion.

Congruent (belief-congruent):
All humans are mammalian. All mammals are animals.
(1) Some humans are not animals. (2) All humans are animals. (3) No valid conclusion. (4) Some humans are animals. (5) No humans are animals.

Incongruent (belief-incongruent):
All Barbaras are reptiles. Some Barbaras are humans.
(1) No valid conclusion. (2) Some humans are not reptiles. (3) No humans are reptiles. (4) All humans are reptiles. (5) Some humans are reptiles.

Appendix B. Examples of subtests of the Kyodai Nx15-

B.1. Verbal intelligence tests

Word completion:
mo□her

Sentence completion:
Tom ( ) Jim are ( ) friends. [from, and, brother, good, or, next]

Antonym or synonym:
heavy [small, light, tired, cotton, soft]

Rearrangement of words:
is, what color, snow [red, black, white, blue, yellow]

B.2. Spatial intelligence tests

Punching a folded paper:

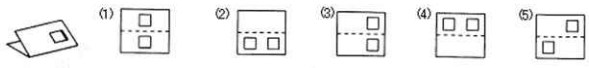
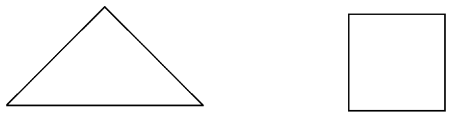


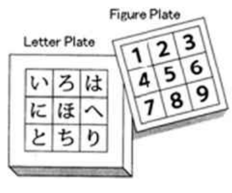
Figure combination:



complete square

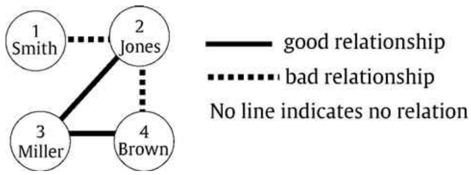
Draw a line indicating how to divide and rearrange the figure in order to form a complete square.

Combination of figure and letter plates:



Which number falls on と, when number 5 in the figure plate is placed on ち in the letter plate?

Sociogram:



Who is the least-related to the others?

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