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SOME MATHEMATICAL ASPECTS OF THE BINET-SIMON TESTS

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Since the Binet-Simon Scale for Measuring the Intelligence of Young Children was first issued, a number of translations into other languages with necessary adaptations of tests have been made and these have been followed by various revisions. These adhere in their main features and plan to the original idea of Binet and Simon.

This was to set tests for different age levels and, by observing the child's successes and failures, to give him a net score for the series which has been called the child's "Mental Age." This score has been taken as an index of the child's intelligence or intellectual status; and comparison of this score with his "Chronological Age" has been used as diagnostic of feeble-mindedness, mental normality, or mental precocity.

The Goddard revision (1911) of the Binet-Simon scale (3)¹ has been used more extensively than any other in this country and may be taken as typical. Five tests are set for each level from 3 to 12 inclusive; and standards for giving these and for scoring success or failure have been more or less definitely worked out. A child is credited with a "basal age" of the highest year for which he passes all the tests. To determine his mental age one year is added for each five tests passed from the higher age levels.

Ideally, mentally normal children of a given chronological age should make a mean mental age score which is approximately equal to their chronological age. It was soon observed by those who used the Binet-Simon Scale in its earlier form that the results obtained were not equally satisfactory for normal chil-

¹ The figures in parenthesis refer to the bibliography at the end of the article.

dren of all ages. Young children tested too high, children over 12 too low, and the best results were obtained for the intermediate ages. In the revisions of the scale which followed various efforts were made to remedy this defect. Tests for other age levels were introduced (11 year tests by Goddard (3) and tests for less than 4 years by Kuhlmann (5)). Certain tests were moved up or down in the scale to different age levels, some new tests were introduced, others discarded, and a stricter technique of giving and scoring the tests was adopted.

Goddard considered the results satisfactory if the mental-age derived was not more than one year above or below the chronological age. By this criterion he considered 78 percent of his results with 1547 children "satisfactory." But his own analysis of these cases (2) showed that these satisfactory results were by no means evenly distributed, as is shown by the following figures:

Chronological Age.....	4	5	6	7	8	9	10	11	12	All
Number of Cases.....	8	114	160	197	209	201	222	166	144	1421
Number Satisfactory.....	5	88	146	179	189	168	170	122	75	1142
Percent Satisfactory.....	63	77	91	91	90	87	76	73	56	80.4

The percentages of satisfactory cases run high for chronological ages 6 to 9 inclusive but fall off at either end of the age series. Other revisions showed similar though perhaps less striking results.

Still more striking were the results with adults and adolescents. Where these results were obtained from institutional cases they were readily accepted as showing a high frequency of mental deficiency and feeble-mindedness but when rather similar results were obtained from factory operatives and high schools some of the disadvantages of the scales became more apparent. Many who made use of the Binet tests seem to have either ignored these difficulties or to have used a lower "passing mark" in interpreting the scores for diagnostic purposes.

Thorndike (10), working over Goddard's results mentioned above and comparing them with later results of other investigators, pointed out clearly the inequalities of these scales and derived a table of "true mental-ages," in which the latter coincide closely with the Binet test mental age up to ten years. Thenceforward the true mental ages for each Binet score are increasingly advanced, giving 13.8 as the true mental age for a Binet score of 11.8. Too little attention seems to have been given to the

reason for these inequalities which lies in the very nature of the scales. A boy of 7 has, in Goddard's revision, some theoretical chance of passing 25 tests beyond the tests set for the seven year level. A boy of 11, on the other hand, has a chance of passing only 5 tests beyond those set for the eleven year level. It is obvious that, unless these 5 tests are easier for the twelve year old boy than any 5 of the 25 tests are for the seven year old boy, the seven year old boy has the better chance of securing credit for tests above his chronological age.

The Stanford Revision (8), prepared by Prof. Lewis N. Terman of Leland Stanford Jr. University and recently issued, is a serious attempt to overcome some of the chief disadvantages of the earlier revisions. In this series there are six tests set for each year level from 3 to 10 years inclusive. Success in each of these tests above the basal age is counted as two months toward the mental-age score. For 12 years there are eight tests, each counting three months, for 14 six, each counting four months, for 16 and 18 there are in each case six tests counting as five and six months respectively. The method and technique of this revision have been worked out much more carefully and stated more clearly than in any earlier revision.

In interpreting the significance of the mental age scores of children of the same or different ages or of the same child at different ages obtained from this revision the intelligence quotient or ratio of mental age score to chronological age ($\times 100$) has been found convenient. The mean intelligence quotient of each age group tested by Terman approximates 100. But this scale also in many cases gives too high a mental age score for the very young children and too low a score for those over 12. It is the purpose of this paper to suggest one method of theoretical treatment which should be useful:

1. In comparing the results obtained with children of different ages from any revision and in interpreting the significance of these mental-age scores or intelligence quotients.

2. In comparing the validity of the results obtained by the use of different revisions.

3. In predicting the results which may be expected from still further revision or alteration.

If the individual tests of the Stanford Revision are given to normal seven year children or the so-called unselected² children

² The definition of "unselected" is uncertain, but this does not affect the argument of this paper.

who are not suspected of marked mental deficiency we find that the average relative frequency with which these children pass these tests begins with a frequency approaching unity for the four year tests and that this percentage decreases steadily for the tests set at higher age levels. If these frequencies are known, it becomes possible to compute the theoretical distribution of basal ages; *i. e.*, to find the probable number who will have a basal age of four years, five years, etc., respectively.

Let us assume for purposes of simplification that this frequency is the same for each of the tests given at any age level (six in the case of the Stanford Revision). The argument remains the same even where they vary considerably. Assume for purposes of argument that the following results are obtained (actual frequencies would have been used but Terman's results had not yet been published when this was written).

Average of relative frequency for each of 4 year tests										0.98	
"	"	"	"	"	"	"	"	"	5	"	0.95
"	"	"	"	"	"	"	"	"	6	"	0.85
"	"	"	"	"	"	"	"	"	7	"	0.75
"	"	"	"	"	"	"	"	"	8	"	0.50
"	"	"	"	"	"	"	"	"	9	"	0.30
"	"	"	"	"	"	"	"	"	10	"	0.10
"	"	"	"	"	"	"	"	"	12	"	0.05

The probability of a given seven year old child having a basal age of four years will take into account (1) the probability that he will pass all of the six tests for the fourth year $(.98)^6$, and (2) the probability that he will not pass all the tests for any subsequent year. The probability that he will not pass all of the five year tests will be $1 - (.95)^6$ and so on for the higher years. The probability P_4 that 4 will be his basal age may be computed as follows:

$$P_4 = (.98)^6 [1 - (.95)^6] [1 - (.85)^6] [1 - (.75)^6] [1 - (.50)^6] [1 - (.30)^6] [1 - (.10)^6] [1 - (.05)^6]$$

Similarly we have:

$$P_5 = (.95)^6 [1 - (.85)^6] [1 - (.75)^6] - \text{etc.}$$

$$P_6 = (.85)^6 [1 - (.75)^6] [1 - (.50)^6] - \text{etc.}$$

On the basis of the above table we have:

$$\begin{aligned} P_4 &= (.886) (.265) (.623) (.822) (.984) (.999) = 0.118 \\ P_5 &= (.735) (.1623) (.822) (.984) (.999) = 0.370 \\ P_6 &= (.377) (.822) (.984) (.999) = 0.305 \\ P_7 &= (.178) (.984) (.999) = 0.175 \\ P_8 &= (.016) (.999) = 0.016 \\ P_9 &= (.001) = 0.001 \\ P_{10} &= 0.000 \end{aligned}$$

$$0.985$$

As a check on this calculation we have:

$$P_0 = (.114) (.265) (.623) (.822) (.984) (.999) = \frac{0.015}{1.000}$$

P_0 being the probability that no one of these basal ages will be attained.

If the average percentages for the six tests of each different age level for children of a given age be respectively p_4 , p_5 , p_6 , p_7 , etc., our calculations become:

$$P_4 = p_4^6 (1-p_5^6) (1-p_6^6) \dots (1-p_k^6)$$

$$P_5 = p_5^6 (1-p_6^6) (1-p_7^6) \dots (1-p_k^6) \text{ etc., and we have:}$$

$$P_n = p_n^6 (1-p_{n+1}^6) (1-p_{n+2}^6) \dots (1-p_{k+1}^6) (1-p_k^6) \quad (A)$$

If we wish to be more exact we may observe the frequency with which children of a given age pass each test and take the product of the six values for any age level and substitute this product for p^6 . This will not materially change the distribution unless the mean variation is large and the argument remains the same. Suppose these products be represented by $q_4, q_5, q_6, \dots, q_k$ and we then have $P_n = q_n (1 - q_{n+1}) (1 - q_{n+2}) \dots (1 - q_{k-1}) (1 - q_k)$ (B).

Having determined the distribution of basal ages we may proceed to the calculation of the probabilities that tests above this basal age will be passed.

If the frequency with which each of these tests are passed is known we may calculate the probability that a certain mental age will be attained.

Assuming, for purposes of illustration, that these frequencies are the same for seven year old children for all six tests of any age level, our calculation proceeds as follows. The probability that all six of the tests will be passed may be ignored since in that case the child would be included among those whose basal age is of this or of a subsequent year. We are therefore concerned with the probability that exactly five, four, three, two, one, or none of this group will be passed.

Suppose each of the tests of any age group be passed with a frequency p , the probability

that exactly	5	will be passed	$= 6p^5 (1-p),$	
"	4	"	$= 15p^4 (1-p)^2,$	
"	3	"	$= 20p^3 (1-p)^3,$	
"	2	"	$= 15p^2 (1-p)^4,$	
"	1	"	$= 6p (1-p)^5, \text{ and}$	
"	0	"	$= (1-p)^6$	(C)

As a check on these calculations we may add p^6 , the probability that all six will be passed, to the sum of these probabilities and our result should be equal to unity. Suppose, for example, that 75 percent. of seven year old children pass each of the seven year tests and we have the probability

that exactly 5 tests will be passed = 0.356

“ “ 4 “ “ “ “ = 0.297

“ “ 3 “ “ “ “ = 0.132

“ “ 2 “ “ “ “ = 0.033

“ “ 1 “ “ “ “ = 0.004

“ “ 0 “ “ “ “ = 0.000

0.822

“ “ 6 “ “ “ “ = 0.178

1.000

If the probabilities for all six tests are not the same, it will not seriously change our results to use the mean probability for the six. Or to be more exact, if these probabilities be p_1, p_2, p_3, p_4, p_5 , and p_6 we have the probability that exactly five tests will be passed equal to $p_1 p_2 p_3 p_4 p_5 (1-p_6) + p_1 p_2 p_3 p_4 p_6 (1-p_5) + p_1 p_2 p_3 p_5 p_6 (1-p_4) + p_1 p_2 p_4 p_5 p_6 (1-p_3) + p_1 p_3 p_4 p_5 p_6 (1-p_2) + p_2 p_3 p_4 p_5 p_6 (1-p_1)$. (D) Similarly the probability that exactly four tests will be passed is equal to:

$$\begin{aligned} & p_1 p_2 p_3 p_4 (1-p_5) (1-p_6) + p_1 p_2 p_3 p_5 (1-p_4) (1-p_6) + p_1 p_2 p_3 p_6 (1-p_4) (1-p_5) + \\ & p_1 p_2 p_4 p_5 (1-p_3) (1-p_6) + p_1 p_2 p_4 p_6 (1-p_3) (1-p_5) + p_1 p_2 p_5 p_6 (1-p_3) (1-p_4) + \\ & p_1 p_3 p_4 p_5 (1-p_2) (1-p_6) + p_1 p_3 p_4 p_6 (1-p_2) (1-p_5) + p_1 p_3 p_5 p_6 (1-p_2) (1-p_4) + \\ & p_1 p_4 p_5 p_6 (1-p_2) (1-p_3) + p_2 p_3 p_4 p_5 (1-p_1) (1-p_6) + p_2 p_3 p_4 p_6 (1-p_1) (1-p_5) + \\ & p_2 p_3 p_5 p_6 (1-p_1) (1-p_4) + p_2 p_4 p_5 p_6 (1-p_1) (1-p_3) + p_3 p_4 p_5 p_6 (1-p_1) (1-p_2) \end{aligned} \quad (E)$$

And we have similar series for three, two, one, and no tests, respectively.

Suppose that $p_1 = .7, p_2 = .7, p_3 = .75, p_4 = .75, p_5 = .8$ and $p_6 = .8$ then the probability

that exactly 5 tests will be passed = 0.357

“ “ 4 “ “ “ “ = 0.298

“ “ 3 “ “ “ “ = 0.132

“ “ 2 “ “ “ “ = 0.032

“ “ 1 “ “ “ “ = 0.004

“ “ 0 “ “ “ “ = 0.000

0.823

$p_1 p_2 p_3 p_4 p_5 p_6$ (the probability that all six will be passed) = 0.176

0.999

It is apparent that these results do not differ materially from those derived from assuming these probabilities all equal to the average, *i. e.* 0.75, as above.

If, therefore, one is to determine the expectations of mental age scores for the seven year children of each basal age group, he must calculate the probabilities that a certain total number of tests beyond the basal year will be passed. To do so, he will calculate as above the probabilities that 5, 4, 3, etc., tests respectively will be passed from each age group. He will tabulate these results and proceed to calculate the probabilities that a certain number will be passed from all groups above the basal age, beginning at the highest.

If the probabilities that 5, 4, 3, etc., tests are passed from the ten year group be respectively q_5, q_4, q_3 , etc., and from the nine year group be r_5, r_4, r_3 , etc., and the probabilities that 10, 9, 8, etc., respectively be passed from the two groups be x_{10}, x_9, x_8 etc., we have:

$$\begin{aligned}x_{10} &= q_5 r_5 \\x_9 &= q_5 r_4 + q_4 r_5 \\x_8 &= q_5 r_3 + q_4 r_4 + q_3 r_5, \text{ etc., and} \\x_7 &= q_4 r_3 + q_3 r_4 \\x_6 &= q_3 r_3\end{aligned}$$

As a check on these calculations, we have $\Sigma_q \Sigma_r \text{ etc.,} = \Sigma_x$ where Σ_q is the sum of $q_5 + q_4 + \dots + q_0$, etc. In a similar way we may calculate the probabilities that 15, 14, 13, etc., tests respectively will be passed from the three year groups 8, 9, and 10. If these probabilities be y_{15}, y_{14}, y_{13} , etc., and those for the 8 year group be s_5, s_4, s_3 , etc., we have:

$$\begin{aligned}y_{15} &= x_{10} s_5 \\y_{14} &= x_9 s_5 + x_{10} s_4 \\y_{13} &= x_8 s_5 + x_9 s_4 + x_{10} s_3, \text{ etc.,} \\&\text{and} \\y_{12} &= x_7 s_5 + x_8 s_4 \\y_{11} &= x_6 s_5 + x_7 s_4 \\y_{10} &= x_5 s_5 + x_6 s_4 \\y_9 &= x_4 s_5 + x_5 s_4 \\y_8 &= x_3 s_5 + x_4 s_4 \\y_7 &= x_2 s_5 + x_3 s_4 \\y_6 &= x_1 s_5 + x_2 s_4 \\y_5 &= x_0 s_5 + x_1 s_4 \\y_4 &= x_0 s_4 + x_1 s_3 \\y_3 &= x_0 s_3 + x_1 s_2 \\y_2 &= x_0 s_2 + x_1 s_1 \\y_1 &= x_0 s_1 + x_1 s_0 \\y_0 &= x_0 s_0\end{aligned}$$

Again we have as a check:

$$\Sigma_x \Sigma_s = \Sigma_y$$

On the basis of the distribution of basal ages derived in our first table, we may proceed to determine the relative distribution of each group according to mental age. Since none attains a basal age of 10, we may assume that those represented by P_0 , *i. e.*,

those not attaining the basal ages given, have a basal age of three years. If we distribute each basal age group according to the relative expectation of passing additional tests we get the following result:

Distribution of 7 year children according to mental-age score (Stanford Revision)

		Basal ages							Total
Mental age score									
yrs.	mo.	3	4	5	6	7	8	9	
9	0							.001	.001
	10						.001		.001
	8					.001	.002		.003
	6				.001	.005	.004		.010
	4			.001	.005	.013	.005		.024
	2			.004	.013	.025	.003		.045
8	0		.001	.012	.028	.036	.001		.078
	10		.004	.027	.047	.038			.116
	8		.008	.047	.059	.030			.144
	6	.001	.014	.065	.059	.018			.157
	4	.002	.020	.070	.046	.007			.145
	2	.003	.022	.061	.028	.002			.116
7	0	.003	.020	.043	.013	.000			.079
	10	.003	.014	.024	.005				.046
	8	.002	.009	.011	.001				.023
	6	.001	.004	.004	.000				.009
	4	.000	.002	.001					.003
	2	.000	.000	.000					.000
6	0								
		.015	.118	.370	.305	.175	.016	.001	1.000

It will be observed that this computation is effected in the case of the basal age 7, for example, by multiplying each of the expectations for passing tests from the 8, 9, and 10 year levels (y_{15} , y_{14} , y_{13} , etc.) by P_7 divided by the sum of these expectations, i. e., $P_7 \div \Sigma y$. Thus $\frac{P_7}{\Sigma y} y_5 = 0.038$, the expectation that 7 year children having a basal age of 7 will pass five tests from the higher age levels and therefore attain a mental-age score of 7 yrs., 10 mos. This gives a "normal" distribution of mental-age scores with a mode of seven years and six months. This would suggest that the assumed frequencies are too high but this does not affect the argument.

In the case of the Goddard revision the determination of the theoretical distribution of mental-age scores would be made in much the same way. Using a similar notation and argument we have formulae, analogous to (A) and (B) above, for the distribution of basal ages as follows:

$$P_n = p_n^6 (1-p_{n+1}^6) (1-p_{n+2}^6) \dots (1-p_k^6) \text{ or}$$

$$P_n = q_n (1-q_{n+1}) (1-q_{n+2}) \dots (1-q_k)$$

Here the probability that five tests will be passed from any age level above the basal age is excluded and for the probability that exactly four tests will be passed from any age level we have (where the relative frequencies for passing each of the tests of this age level are all equal to p) $5p^4(1-p)$,

for exactly 3 tests $10p^3(1-p)^2$,

" " 2 " $10p^2(1-p)^3$,

" " 1 " $5p(1-p)^4$, and

" " 0 " $(1-p)^5$.

These are, of course, analogous to (C) above.

Where these probabilities for any age level are not equal (p_1, p_2, p_3, p_4 , and p_5) we have the probability that exactly four tests will be passed equal to $p_1p_2p_3p_4(1-p_5) + p_1p_2p_3p_5(1-p_4) + p_1p_2p_4p_5(1-p_3) + p_1p_3p_4p_5(1-p_2) + p_2p_3p_4p_5(1-p_1)$, analogous to (D) above. Similarly the probability that exactly three tests will be passed is equal to $p_1p_2p_3(1-p_4)(1-p_5) + p_1p_2p_4(1-p_3)(1-p_5) + p_1p_3p_4(1-p_2)(1-p_5) + p_2p_3p_4(1-p_1)(1-p_5) + p_1p_2p_5(1-p_3)(1-p_4) + p_1p_3p_5(1-p_2)(1-p_4) + p_2p_3p_5(1-p_1)(1-p_4) + p_1p_4p_5(1-p_2)(1-p_3) + p_2p_4p_5(1-p_1)(1-p_3) + p_3p_4p_5(1-p_1)(1-p_2)$. This is analogous to (E) above and we have similar series for two, one, and no tests.

For illustration of this method with the Goddard revision I am indebted to Mr. E. A. Doll of the Vineland Laboratory for empirical frequencies of so-called unselected children on each of the tests of this revision. I have made use of the data for the seven year group (39 children with average chronological age 7.4 years), the ten year group (68 children with average chronological age 10.5 years) and the twelve year group (69 children with average chronological age 12.5 years).

A theoretical distribution of mental-age scores by this method based on the observed mean frequencies with which children of these groups passed the individual tests gives results which correspond closely with the actual results in the case of these children, as will be observed from the following comparative table:

Age Groups	Number of Cases	Mean Chronological Age	Mean Mental-Age Scores	
			Actual	Calculated
7	39	7.4	7.2	7.3
10	68	10.5	10.6	10.7
12	69	12.5	10.8	10.9

It has been customary in working upon any revision or modification of the Binet-Simon tests to rescore individual records or re-test children according to the revised or modified scale. It would appear that, where no new tests were introduced, as for example in Doll's Abbreviated Scale, it would be a fairly reliable method to test the new scale by distributing the mental-age scores theoretically on the basis of frequencies already observed. Where new tests were introduced, it would be only necessary to determine empirical frequencies for these tests and introduce them into a theoretical treatment along with the data previously obtained for the tests which were not new.

As an example of this treatment Doll's Abbreviated Scale (1) gives for the 39 children of the seven year group mentioned above a mean mental-age score of 7.0 and for the 68 children of the ten year group a mean mental-age score of 9.6. Doll's actual results on other children give 7.0 and 9.7 for these age groups.

In the case of the Stanford Revision this method must be somewhat modified where tests above the 10 year level are involved. The argument, however, remains the same. In calculating the distribution of basal ages one must use p^8 and $(1-p^8)$ in place of p^6 and $(1-p^6)$ for the 12 year level. In calculating the expectation of passing beyond the 10 year level for distributing the mental age scores a new complication arises. The tests are weighted differently since a different value in months is given to the tests of different age levels. For this reason it is convenient to reduce each to months. A boy passing 5 eighteen year tests and 4 sixteen year tests scores $(5 \times 6) + (4 \times 5)$ or 50 months. This reduction to months may be continued into the age levels below 12 or after deriving the expectation from the 12, 14, 16, and 18 year levels one may reduce them to the equivalent of two month tests. Thus for 80 and 81 one may substitute 40, and for 78 and 79, 39, since the final expectations and distributions derived are to be on a two months' basis. Of course p_{40} in this case would equal $p'_{80} + p'_{81}$, and $p_{39} = p'_{78} + p'_{79}$.

The method can also be easily adapted to the abbreviated Stanford Scale (tests marked by asterisk) by an appropriate weighting of the tests involved. The theoretical correlation between this and the complete scale can thus be easily deter-

ined on the basis of empirical frequencies without the necessity of rescoring individual results or of testing additional children.

The term "mental-age score" rather than "mental-age" has been used in this treatment because it is objective and concrete, a qualitative and quantitative measure of a child's reactions to a series of tests given and scored in a standardized manner. Confusion has arisen because the term mental-age has been used by many writers in two senses which are not easily distinguished by the reader. On the one hand it is held to signify a quantitative expression of the child's intellectual status or intelligence level in terms of the average child. To say in this sense that a seven year child has a mental-age of eight years is to say that the child's intellectual status is equivalent to that of an average eight year child and above that of the average child of his own age. On the other hand the term mental-age has been used to signify the score attained by the child in a series of Binet-Simon tests. Even if one grants the psychological advantage of the concept mental-age in the first of these meanings, which may well be challenged except for popular use, one is only justified in using these terms interchangeably by assuming a perfect correlation between this score as obtained in the case of any child and the measure of that complex more-or-less undefined something which we call his intelligence or intellectual status. It is much more in keeping with our present limited knowledge of intelligence not to make this assumption and, except for popular use, to avoid the use of the term mental-age. As Witmer has pointed out (11), these tests show a child's "performance level" and one should speak of his mental age score rather than his mental age. It is confusing to use the term mental age in any sense other than that of a score or performance level in making the statement that "normal five year children have a mental age of six years." (Approximately the average score by the Goddard revision). Yerkes has overcome this ambiguity by scoring the child's performance on his point scale. Terman's term "intelligence quotient" also will avoid confusion if one does not press too strongly the assumption that the average child's intelligence quotient should be 100, or the idea that intelligence alone has been tested.

In other words the result of the child's performance is a score. To judge of the child's intellectual status or intelligence it is

necessary to interpret this objective result. His high score may be due to good health, good training, good intelligence in one or more performances involving different mental abilities or functions or in a combination of all of these. A low score must also be interpreted rather than accepted without question as an infallible index of low intelligence. It may, for example, be due to the arrangement of the tests in the scale as when a twelve year old boy is tested by the Goddard revision without using tests beyond the 12 year level. The chances are against his obtaining an I. Q. of 100 as he has no tests offered him for raising his score above 12 years.

Otis has already pointed out (6 and 7) that the relative frequencies obtained by those who have administered Binet-Simon tests are objective data which may be treated mathematically. These methods, whether applied to the Goddard, Stanford, or similar revisions, or adapted to the Yerkes-Bridges scale, should be developed so that these data may be considered on their own merits and not on any *a priori* assumption of "the validity of the scale," the nature of mental deficiency, etc.

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