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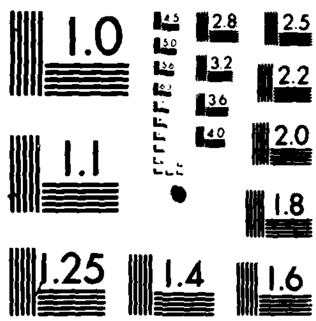

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RULE SPACE, THE PRODUCT SPACE OF TWO SCORE COMPONENTS IN SIGNED-NUMBER SUBTRACTION: AN APPROACH TO DEALING WITH INCONSISTENT USE OF ERRONEOUS RULES

KIKUMI K. TATSUOKA

ROBERT BAILLIE

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Copies of this report may be
requested from:

Kikumi K. Tatsuoka
252ERL
103 S. Mathews
University of Illinois
Urbana, IL 61801

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Students' responses to a 40-item test on signed-number subtraction are viewed as consisting of two different components, the sign and absolute value parts. Each component is scored zero-one for wrong or correct of the corresponding part of the answers. The traditional scoring yields a score

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of one only when both components have scores of one. By taking the values of the Extended Caution Index for the absolute value component as x-axis and those for sign component as y-axis, all pairs of component response patterns produced by consistent or inconsistent application of some kind of rules or random errors are mapped into the ECI product space. A simulation study showed that the response patterns generated by changing the binary score of any one item in the response patterns of an erroneous rule cluster together in the ECI product space. Moreover, the response patterns resulting from the same kind of misconceptions fall closer together than those resulting from very different kinds. This property of the ECI product space opens up a promising way to handle numerous numbers of "bugs" or rules quantitatively. But the ECIs are not defined in the cases of perfect scores and all zeros. There are often a considerable number of incomplete rules (e.g., all signs of the responses are right but absolute value parts are taken by some erroneous rule). The relationship between these incomplete, partially-right rules and the right rule or between other rules and the right rule cannot be discussed in this space at the present.

Abstract

Students' responses to a 40-item test on signed-number subtraction are viewed as consisting of two different components, the sign and absolute value parts. Each component is scored zero-one for wrong or correct of the corresponding part of the answer. The traditional scoring yields a score of one only when both components have scores of one. By taking the values of the extended caution index for the absolute value component as the x-axis and those for the sign component as the y-axis, all pairs of component response patterns produced by consistent or inconsistent application of various rules or random errors are mapped into the ECI product space. A simulation study showed that the response patterns generated by changing the binary score of any one item in the response patterns of an erroneous rule cluster together in the ECI product space. Moreover, the response patterns resulting from the same kind of misconceptions fall closer together than those resulting from very different kinds. This property of the ECI product space opens up a promising way to handle large numbers of "bugs" or rules quantitatively. But the ECIs are not defined in the cases of perfect or zero scores. Typically, there are many incomplete rules (e.g., all signs of the responses are right but absolute value parts are taken by some erroneous rule).

Introduction

Tatsuoka and Linn (1982) have recently introduced a group of new indices, extended caution indices for individual i (ECI_i), by extending Sato's original caution index (1975) into the context of item response theory (IRT). The caution index (C_i) is designed to identify anomalous binary response patterns to test items and to extract information not contained in the total score. Of course, several authors have developed appropriateness indices in conjunction with IRT (Wright, 1977; Levine and Rubin, 1979), but Tatsuoka and Linn's ECI_i has a unique feature different from appropriateness indices. When estimating the parameters of IRT models is not possible, C_i can be used instead of the ECIs, without loss of conceptual continuity. The item response curve, and test and group response curves used in defining ECI can be replaced by standard summary statistics based on observed item responses such as the number or proportion of people in a norm group answering an item correctly. C_i is designed for using such standard statistics based on sampling theory. Indeed, Harnisch and Linn (1981) used C_i for analyzing a NAEP dataset (National Assessment of Educational Progress) and successfully diagnosed curriculum differences and school differences within a school district. However, Rudner (1982) found that IRT-based indices detected aberrant response patterns more efficiently than those based on summary statistics. A recent paper by Tatsuoka and Tatsuoka (1982c) warns that there may be an upper limit to any personal indices' capability to detect aberrant response patterns. The detection rates by ECIs and one of the appropriateness measures are about 60% correct identification of aberrance, and 20% "false alarms," i.e., normal response patterns labelled aberrant. The result agrees with Rudner's findings. It implies that further investigation of the behaviors of ECIs may be needed.

This paper introduces a new application of ECIs for studying a variety of students' misconceptions, which produce aberrant response patterns. By so doing, we may be able to uncover a different aspect of characteristics of ECIs. When tests are designed to measure the outcome of learning processes, looking into a whole response pattern to the test items often provides useful information to diagnose the student's state of knowledge (Birenbaum & Tatsuoka, 1980; Birenbaum & Tatsuoka, 1982a). The ECI values are determined by using response patterns and provide desirable information for diagnostic purposes.

An error diagnostic system for signed number arithmetic (SIGNBUG) has been developed by Tatsuoka and Baillie (1982) and it has successfully diagnosed quite a number of erroneous rules of operation. Similar diagnostic system for arithmetic such as whole number subtraction problems (Brown & Burton, 1978) have also found hundereds of erroneous rules resulting from incomplete knowledge or some kind of misconception ("bug") possessed by the students. But these systems are expensive and time consuming to construct. Besides, they can be used in only very specific domains of arithmetic. Tatsuoka and Linn (1982) briefly discussed using one of the five ECIs to detect the erroneous rules of operation in signed-number arithmetic. The ECIs have two possible advantages over previously considered approaches. First, unlike the individual consistency index (Tatsuoka & Tatsuoka, 1981, 1982b), ECIs do not require repeated measrues. Second, application of ECIs is not restricted to specific content domains such as signed numbers computations or whole number arithmetic. Moreover, the number of erroneous rules can sometimes become so large as to require some quantitative methods to classify them and to examine their relationships. Tatsuoka (1981) has tried to quantify the seriousness of misconceptions by ascertaining which level of the procedural steps it was that a student missed. Her approach is content specific and may be useful only for very simple problem domains.

This paper discusses a more general quantitative approach by utilizing the advantages of IRT-based ECIs. All erroneous rules of operation will be expressed as points in a geometric space (called "rule space"). Rule space is useful in handling large numbers of bugs and for examining their psychometric properties such as "stability" or "transitivity" of bugs (Tatsuoka, 1982). This new approach will be illustrated with the test data obtained from a 40-item test of signed-number subtraction problems. Moreover, the relationships between rules and their partially consistent application to the test items will be illustrated with simulated data in rule space.

Method and Procedure

A Brief Introduction of the Extended Caution Indices

The caution index for subject i is defined as the complement of the ratio of two covariances. The numerator of the ratio is the covariance of observed row vector, $\underset{\sim}{y_i} = (y_{i1},\ldots,y_{in})$ in the score matrix (y_{ij}), [$i = 1,\ldots,N$, $j=1,\ldots,n$ where N is the number of subjects and n the items], and the column-sum vector, $y_{.} = (y_{.1}, y_{.2},\ldots, y_{.n})$. The denominator is the covariance of the corresponding scores rearranged as a reverse Guttman vector $\underset{\sim}{M_i^s} = (M_{i1}, M_{i2},\ldots, M_{in})$ and the column-sum vector $\underset{\sim}{y_.}$. Thus C_i is given by Equation (1).

$$C_i = 1 - \frac{(\underset{\sim}{y}_i - \underset{\sim}{P}_{i.}\ ,\ \underset{\sim}{y}_{.} - \underset{\sim}{P}_{..})}{(\underset{\sim}{M}_i^s - \underset{\sim}{P}_{i.}\ ,\ \underset{\sim}{y}_{.} - \underset{\sim}{P}_{..})} = 1 - \frac{\mathrm{cov}(\underset{\sim}{y}_i\ ,\ \underset{\sim}{y}_{.})}{\mathrm{cov}(\underset{\sim}{M}_i^s\ ,\ \underset{\sim}{y}_{.})} \tag{1}$$

The values of ECIs are calculated by first constructing a probability matrix with elements P_{ij}. In practice, the P_{ij} can be replaced by $\hat{P}_{ij}$, whose values are obtained by substituting estimated item and person parameters in the logistic function.

One of the ECIs, ECI4, is defined by taking the ratio of two covariances of which the numerator is the covariance of the ith row vector in the score matrix (y_{ij}) and that in the probability matrix (P_{ij}), which are denoted by $\underset{\sim}{y}_i$ and $\underset{\sim}{P}_i$, respectively. The denominator is the covariance of the column-sum vector of (P_{ij}) which is denoted by $\underset{\sim}{G} = (G_{.1}, G_{.2}, \ldots, G_{.n})$, and $\underset{\sim}{P}_i$. The following Equation (2) is the fourth index ECI4.

$$\mathrm{ECI4} = 1 - \frac{\mathrm{cov}(\underset{\sim}{y}_i\ ,\ \underset{\sim}{P}_i)}{\mathrm{cov}(\underset{\sim}{G}\ ,\ \underset{\sim}{P}_i)} \tag{2}$$

The second ECI is ECI2 of which the denominator is the same as that of ECI4, but the numerator is the covariance of $\underset{\sim}{y}_i$ and $\underset{\sim}{G}$ and given in the following equation (3).

$$\mathrm{ECI2} = 1 - \frac{\mathrm{cov}(\underset{\sim}{y}_i\ ,\ \underset{\sim}{G})}{\mathrm{cov}(\underset{\sim}{P}_i\ ,\ \underset{\sim}{G})} \quad . \tag{3}$$

Unlike the caution index, the numerator of ECI4 is the covariance of the observed vector $\underset{\sim}{y}_i$ and the probability vector $\underset{\sim}{P}_i$ at the fixed level i, which is not a group dependent vector. As a result, ECI4 should be sensitive to the anomalous response patterns relative to the anomaly of response patterns in comparison with the row vector $\underset{\sim}{P_i}$ at the level θ_i. On the other hand, the identical denominator, $(\underset{\sim}{G}, \underset{\sim}{P_i})$ of ECI2 and ECI4 can be considered as a standardized scaling factor and the difference between the two indices comes from the numerators $\mathrm{cov}(\underset{\sim}{y_i}, \underset{\sim}{P_i})$ and $\mathrm{cov}(\underset{\sim}{y_i}, \underset{\sim}{G})$. In other words, the numerator of ECI2 is proportional to the cosine of the angle between the two vectors $\underset{\sim}{y_i}$ and $\underset{\sim}{G}$ while the numerator of ECI4 is proportional to cosine of that between $\underset{\sim}{y_i}$ and $\underset{\sim}{P_i}$ in n items space. Therefore, the difference between ECI2 and ECI4 can be said to lie in whether the response pattern of the observed vector $\underset{\sim}{y_i}$ conforms better to the pattern of vector $\underset{\sim}{P_i}$ or that of the group average vector G. Tatsuoka and Linn (1982) demonstrated briefly that ECI4 is moderately effective in spotting erroneous rules of operation. However, ECIs are θ-dependent measures and have a strong tendency to give inflated values at both the extremely high and low total scores. In order to avoid the undesired property of ECIs, Tatsuoka and Tatsuoka (1982c) derived the expectations and variances of ECI4 and ECI2 and standardized them. The standardized ECIs are given by Equations (4) and (5).

$$\text{(4)} \qquad ECI4_z = \frac{n\,\mathrm{cov}(\underset{\sim}{P_i} - \underset{\sim}{y_i}, \underset{\sim}{P_i})}{\left[\sum_{j=1}^{n} \sigma_{ij}^2 (\underset{\sim}{P_i} - \underset{\sim}{T_i})^2\right]^{1/2}}$$

$$\text{(5)} \qquad ECI2_z = \frac{n\,\mathrm{cov}(\underset{\sim}{P_i} - \underset{\sim}{y_i}, \underset{\sim}{G})}{\left[\sum_{j=1}^{n} \sigma_{ij}^2 (\underset{\sim}{G_j} - \underset{\sim}{G})^2\right]^{1/2}}$$

nent response patterns: A new scoring procedure

ι 40-item free response test that comprises four parallel subtests ;ned-number subtraction problems was administered to 172 eighth 's at a local junior high school. The traditional scoring of right ıng answers was decomposed into a two-component scoring procedure ;olute-value and sign parts of the responses. The signs of the ıses to n items were scored right or wrong and so were the absolute ı. Therefore, a regular set of responses to n items was decomposed wo binary response patterns related to the sign component and the ıte-value component. The regular response patterns are element- ıultiplications of the two component response patterns. Suppose we hree responses to 10 items resulting from the following four ous rules.

ule 1: The student uses the right rule for addition problems. subtraction problem, he/she changes the signs of the number in the heses first, then converts the subtraction into an addition problem he right conversion.

$$-6 - (-10) = -6 - (+10) = -6 + (-10)$$

ule 2: The student uses a wrong rule for addition. He/she always cts the smaller absolute value from the larger absolute value and the signs of the first number in the answer. The student converts ıction to addition problems correctly, then consistently applies me erroneous rule to the new addition problem.

ule 3: The addition problems are answered by the right rule. ıction problems are converted by a wrong rule -- by simply changing ıeration sign minus, - , to plus, + , except for L-S (e.g., 8-6) ·L (e.g., 6-8) item types. The student knows how to get answers for these two item types without converting them to addition problems. He/she uses the right addition rule for the new addition problems of the other eight item types.

Rule 4: The student always subtracts the smaller absolute value from the larger one and takes the sign of the number with the larger absolute value in the answer. The conversion of subtraction problems to addition is omitted and the difference between addition and subtraction of two signed numbers seems to be ignored.

Table 1 summarizes the four pairs of binary vectors and responses yielded by the four rules. As can be seen in Table 1, the elementwise

Insert Table 1 about here

multiplications of the two component score vectors yield the binary score vector of regular scoring. The response patterns scored by the regular scoring procedure of Rules 2 and 4 are identical but the sign component score vectors are different. Tatsuoka and Tatsuoka (1981) showed that all erroneous rules discovered so far are uniquely represented by the two component score vectors with the 10 items of subtraction problems. Therefore, the two component-response patterns are subjected to the estimation of item and person parameters separately by GETAB (Baillie, 1980).

Appendices I and II are summary lists of the estimated item parameters for the two sets of binary response patterns obtained from the 40-item subtraction test.

Table 1

The Binary Response Patterns of Three Different Scorings Generated by Three Erroneous Rules

Items	Rule 1		Rule 2		Rule 3		Rule 4	
	Responses	R* S* A*	Responses	R S A	Responses	R S A	Responses	R S A
-3 - (-7) = +4	-10	0 0 0	-4	0 0 1	-10	0 0 0	-4	0 0 1
-2 - 8 = -10	-10	1 1 1	-6	0 1 0	-10	1 1 1	+6	0 0 0
5 - (-12) = +17	-7	0 0 0	+7	0 1 0	-7	0 0 0	-7	0 0 0
-11 - +8 = -19	-19	1 1 1	-3	0 1 0	-3	0 1 0	-3	0 1 0
9 - 4 = +5	+5	1 1 1	+5	1 1 1	+5	1 1 1	+5	1 1 1
-15 - (-9) = -6	-24	0 1 0	-6	1 1 1	-24	0 1 0	-6	1 1 1
-13 - 5 = -18	-18	1 1 1	-8	0 1 0	-18	1 1 1	-8	0 1 0
8 - (-6) = +14	+2	0 1 0	+2	0 1 0	+2	0 1 0	+2	0 1 0
-5 - +11 = -16	-16	1 1 1	-6	0 1 0	+6	0 0 0	+6	0 0 0
1 - 10 = -9	-9	1 1 1	+9	0 0 1	-9	1 1 1	+9	0 0 1
Total Scores		6 8 6		2 8 3		4 7 4		2 5 4

*R Regular Scores
*S Sign-Component Scores
*A Absolute-Value-Component-Scores

Rule Space

A rule space is defined as a geometric representation of the rules used by the students. Let $ECI4^s_{iz}$, $i=1,\ldots,N$ be the values of standardized ECIs obtained from the sign-component patterns and $ECI4^a_{iz}$, $i=1,\ldots,N$ be from the absolute-value component patterns. As a result, a pair of two real numbers is associated with each student. However, since ECIs are essentially a ratio of two covariances, they cannot be defined when the scores are either all ones or all zeros. It is impossible to assign a finite number to the response patterns yielded by using the right rule. So we omit the students who answered all the items right or all the items wrong in this study.

A plot of the values of ECI^a_{iz} (hereafter the i will be omitted) against the absolute-component true scores for 100 students (excluding all zeros and all ones) and for the 21 most popular erroneous rules which are produced by a variety of misconceptions, is given in Figure 1.

Insert Figure 1 about here

The erroneous rules are marked by a small circle "o" while the real students are marked by "+". Each point in Figure 1 represents a absolute-component response pattern for the 40 items. If a student responds to the items by applying erroneous Rule 1 explained in Table 1 consistently throughout the test, then his component response patterns yield the same value of $ECI4^a_z$ and true score for the absolute value component as those produced by Rule 1 and his point in Figure 1 coincides with the point of Rule 1. If the student does not apply his or her rule perfectly consistently but answers one or two items randomly, then his or her component response pattern doesn't match that produced by applying the rule consistently. The values of the true

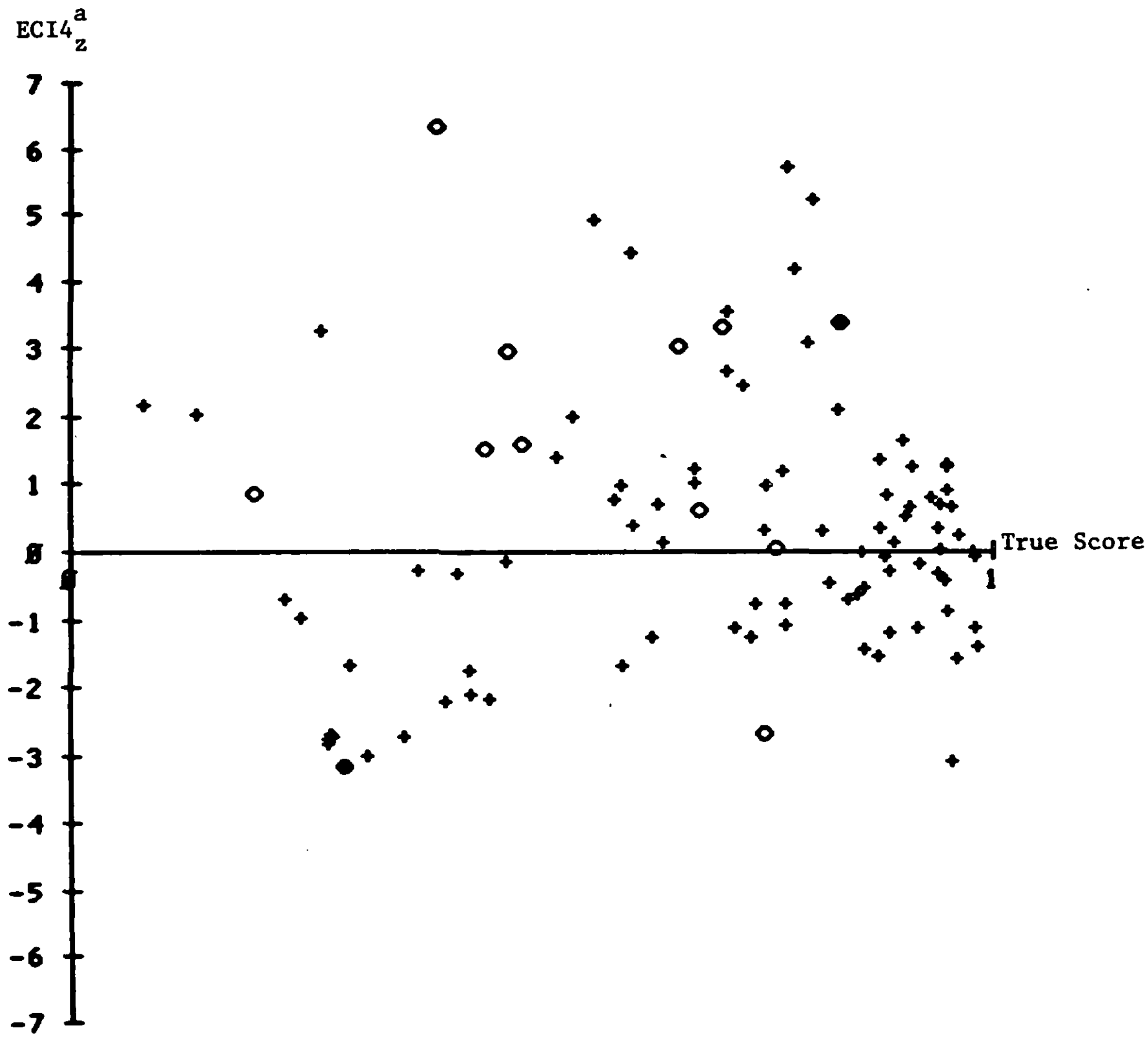

Figure 1: Plot of $ECI4_z^a$ Against True Scores for Absolute Value Component, Real Data ("+") and Erroneous Rules ("0").

scored and $ECI4_z^a$ associated with the student's inconsistent response patterns do not coincide with the values yielded by the rule. Given below in Figure 2 is the sign component, obtained by the same manner as for the absolute-value component patterns.

Insert Figure 2 about here

As can be seen in both the figures, some erroneous rules represented by "o" are found near the x-axis and a considerable number of aberrant response patterns produced by real students "+" is seen outside of erroneous rules "o". It yields the same result -- the low detection rates of aberrant response patterns by personal indices -- as Rudner (1982) and Tatsuoka and Tatsuoka (1982a) found in their studies.

Figure 3 is a plot of the sign-component true scores against absolute-value component true scores. The cluster near the top right corner in Figure 3 represents the students who executed the right rule for responding to the items with different extents of consistency as discussed in Tatsuoka and Tatsuoka (1981).

Insert Figure 3 about here

The ten points on the broken line perpendicular to the x-axis at $\theta = .292$ in Figure 3 have the same sign component response patterns. It means that their source of errors may be identical with respect to understanding of the absolute-value operation but not with respect to the sign operation. For example, since the distance of the two points (rules 16 and 32) is very small, their sources of misconception may be closely related with one another. In order to investigate this question, a simulation study was carried out.

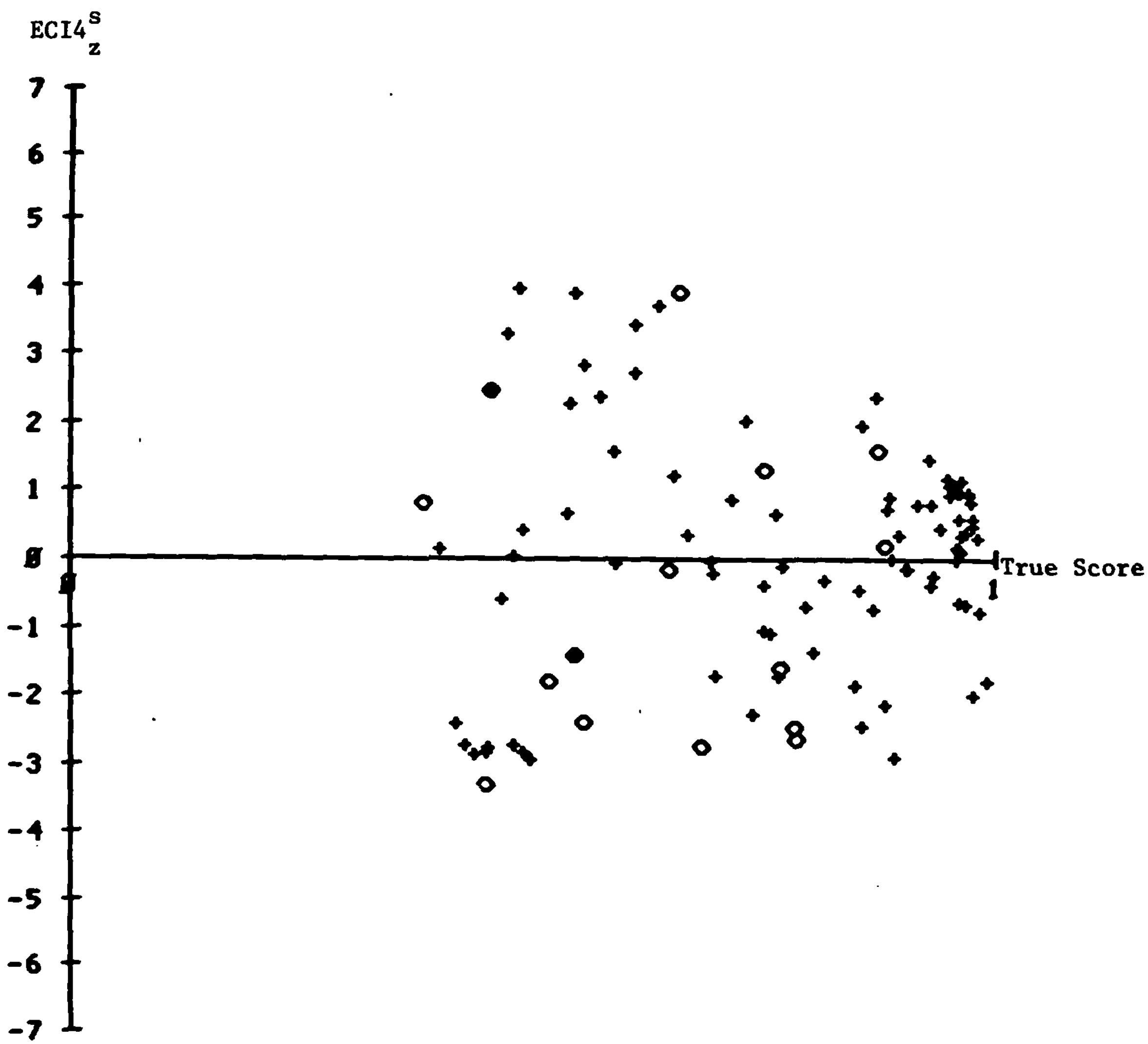

Figure 2: Plot of $ECI4_z^s$ Against True Score for Sign Component Real Data ("+") and Erroneous Rule ("O").

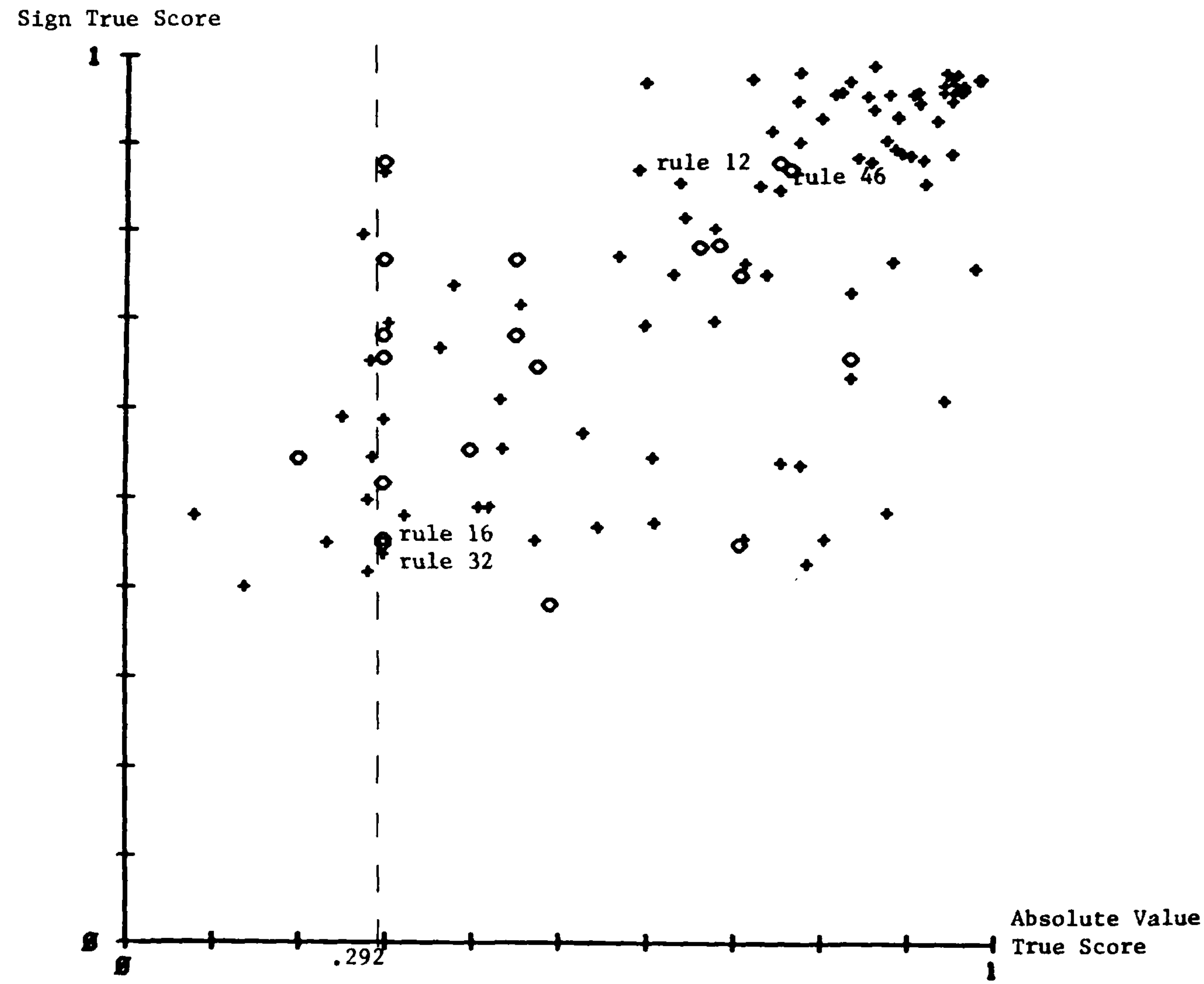

Figure 3: Plot of True Score for Absolute Value Component Against Sign Component, Real Data ("+") and Erroneous Rules ("O").

Procedures for Generating Simulated Inconsistent Responses Around a Rule

The sign-component pattern of Rule 1 given in Table 1 is

$$\underset{\sim}{s}^1 = [0101111111] \quad .$$

If the student uses Rule 1 inconsistently, then his/her responses to the 10 items in each parallel subtest will no longer match the response pattern $\underset{\sim}{s}^1$. Depending on his/her degree of consistency, possibly one or two items out of the 10 will be off from $\underset{\sim}{s}^1$ in at least one subtest. We generate 10 vectors in each of which exactly one element (the ith; i=1,2,...,10) is different from the corresponding element of $\underset{\sim}{s}^1$ (i.e., is its complement) and call them $\underset{\sim}{s}^1(i)$, i=1,2,...,10. If Rule 1 is consistently applied throughout the test, then the four response patterns from the four parallel subtests must be identical. Since a few items in the first subtest were deleted because of large standard errors of estimate by the maximum likelihood procedure used in the computer program GETAB (see Appendix I), the last three subsets were used for generating simulated data for the 31 students as follows:

The first "student's" responses to the four parallel blocks of 10 items each consist of four replications of $\underset{\sim}{s}^1$ itself. The responses of the remaining 30 "students" to the first block of 10 items are likewise $\underset{\sim}{s}^1$ without modification. However, the responses to the second through fourth blocks of 10 items are modified for the first, second and third subgroups of 10 "students" each in the following manner. For the first subgroup (i.e., "students" 2 through 11), the responses to the second block of 10 items are represented by $\underset{\sim}{s}^1(1), \underset{\sim}{s}^1(2), \ldots, \underset{\sim}{s}^1(10)$, while the third and fourth blocks remain "responded to" by Rule 1 to yield two replications of $\underset{\sim}{s}^1$. For the second subgroup ("students" 12 through 21), the responses to the third block of 10 items become $\underset{\sim}{s}^1(1)$, $\underset{\sim}{s}^1(2), \ldots, \underset{\sim}{s}^1(10)$, while those to the second and fourth blocks are $\underset{\sim}{s}^1$ itself. For the third subgroup ("students" 22 through 31), the fourth-blocks responses become $\underset{\sim}{s}^1(i)[i=1,2,\ldots,10]$ while the responses to blocks 2 and 3 remain as $\underset{\sim}{s}^1$. Table 2 shows the 40-element response patterns generated for the 31 "students," for both the sign and absolute-value components. The 31 ECI4 values, including the perfect pattern by Rule 1 as the first vector, were calculated.

Insert Table 2 about here

The same procedure was repeated for the absolute-value component patterns. Thus, two sets of 31 ECI4, one for the sign component, the other for the absolute-value component patterns, are obtained. Figures

Insert Figures 4, 5 and 6 about here

4, 5, and 6 show that the 30 non-consistent (or partially consistent) response patterns plus the perfect pattern by a rule cluster together no matter which axes are chosen in plotting. This implies that each erroneous rule has in its vicinity its "non-consistent" response patterns -- the responses yielded by partially consistent application of the rule -- and they may form a unidimensional set of points like the cluster near the right rule in Figure 3. It confirms the results demonstrated in Tatsuoka and Tatsuoka (1981) and Birenbaum and Tatsuoka (1982a, b), which have investigated the effects of misconceptions on the dimensionality of a dataset and concluded that a unidimensional dataset in signed-number subtraction problems suggests a state of knowledge enabling a student to fairly consistently apply the right rule in responding to the test items. This can be interpreted to mean that a student at a certain state of knowledge produces a particular erroneous

Table 2

Composition of Simulated Data Representing

Inconsistent Response Patterns Around Rule 1

	sign component		absolute value component
1.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}\ ]$	1.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}\ ]$
2.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(1)} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}\ ]$	2.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(1)} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}\ ]$
3.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}_{(2)} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}\ ]$	3.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(2)} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}\ ]$
⋮		⋮	
11.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(10)} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}\ ]$	11.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(10)} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}\ ]$
12.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(1)} \mid \underset{\sim}{s}^{1}\ ]$	12.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(1)} \mid \underset{\sim}{a}^{1}\ ]$
13.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(2)} \mid \underset{\sim}{s}^{1}\ ]$	13.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(2)} \mid \underset{\sim}{a}^{1}\ ]$
⋮		⋮	
21.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(1)}\ ]$	21.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(1)}\ ]$
22.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(2)}\ ]$	2.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(2)}\ ]$
⋮		⋮	
31.	$[\ \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1} \mid \underset{\sim}{s}^{1}_{(10)}\ ]$	31.	$[\ \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1} \mid \underset{\sim}{a}^{1}_{(10)}\ ]$

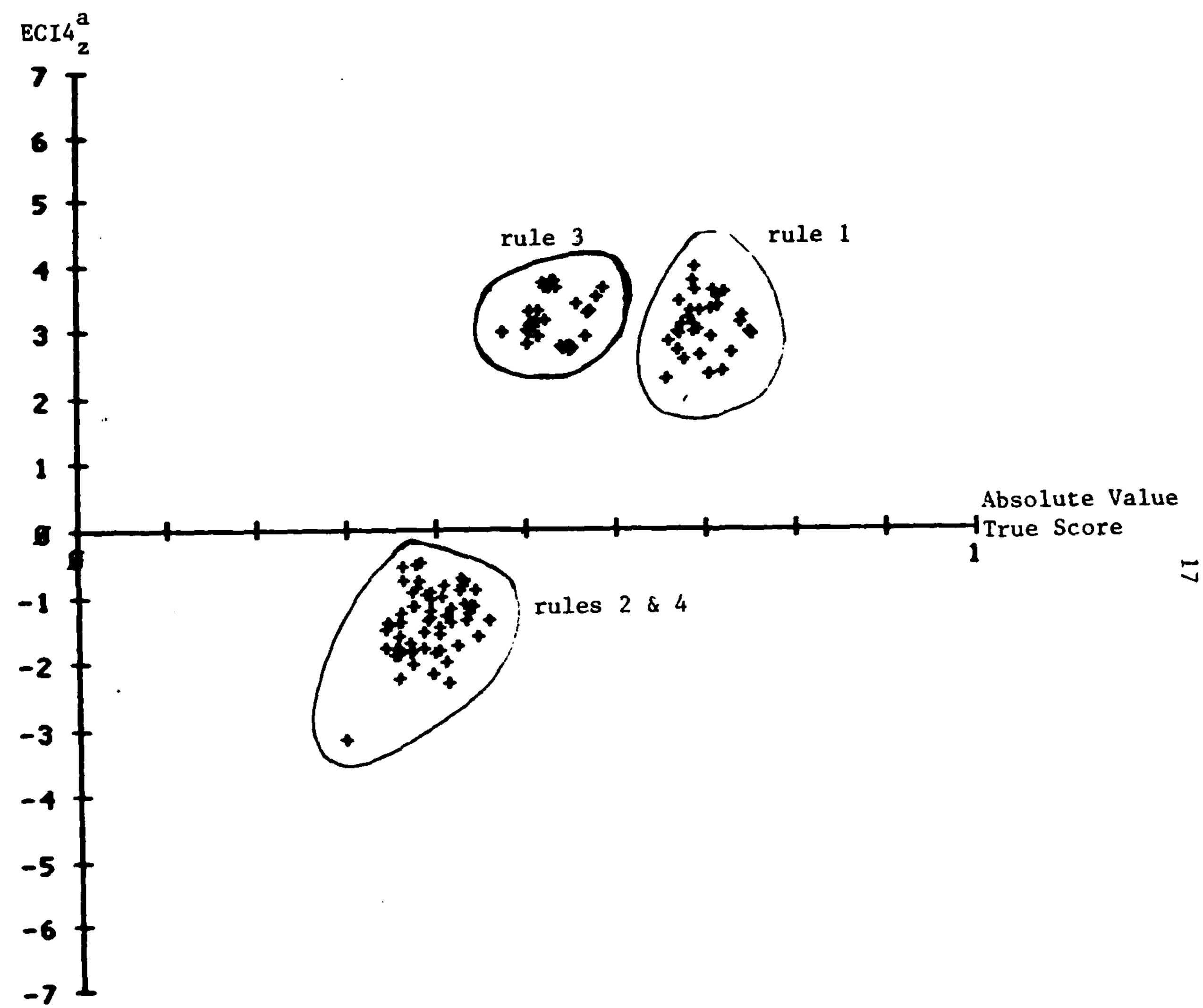

Figure 4: Plot of the Four Clusters Consisting of Inconsistent Responses Around Rules 1, 2, 3 and 4 in Table 1 for Absolute Value Component.

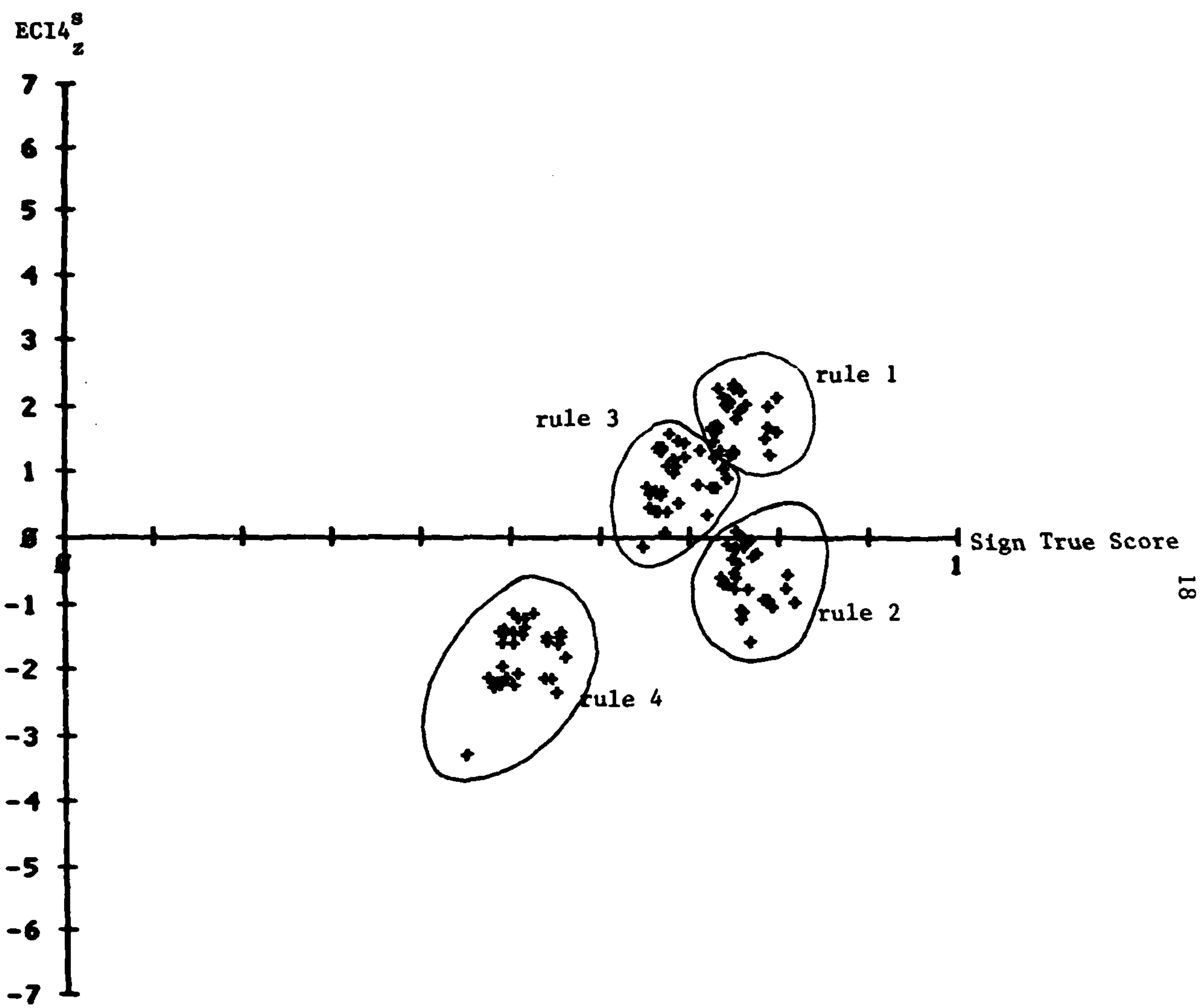

Figure 5: Plot of the Four Clusters Consisting of Inconsistent Responses Around Rules 1, 2, 3 and 4 in Table 1 for Sign Component.

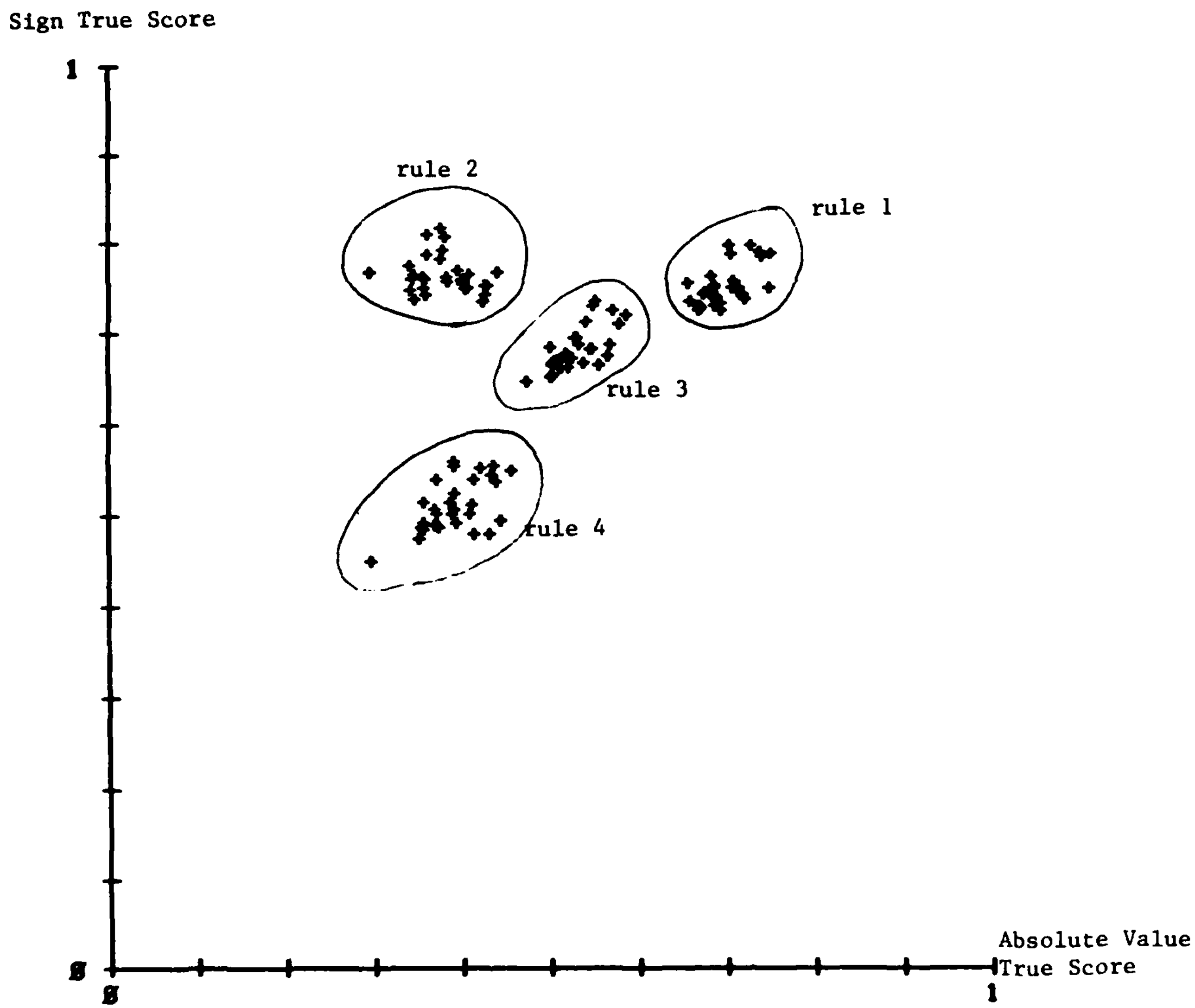

Figure 6: The Clusters of Inconsistent Responses Around Rules 1, 2, 3 and 4 in Table 1.

his knowledge level rises, he starts using the right rule
l consistency (Tatsuoka, 1982). Finally, his responses
and more consistent and reach the right rule, represented by
ht corner in the plot in Figure 3. The phenomenon was
served in several datasets collected at various different
ime of a three year follow-up study of signed-number
which is summarized in Tatsuoka (1982).
cing Figure 1 on top of Figure 4, we are able to find a few
ose absolute-value component patterns fall in one of the four
The error analyses on these responses confirmed that they are
uced by applying each rule with partial consistency.
ur erroneous rules given in Table 1 and the non-consistent
eighboring each of them form four distinctly different
can be seen in Figures 4, 5 and 6. However, Rules 12 and
and 32 (for a more detailed description, see Tatsuoka &
981) marked in Figure 3 produce only two clusters as seen in
'et, when plotted in terms of the absolute-value and sign
four distinctly different clusters are formed in the rule
d by the absolute value true scores and $ECI4^{a}_{1z}$ as shown in

<u>Insert Figures 7 & 8 about here</u>

nt that the values of ECIs are capable of separating
terns that have very close true scores.

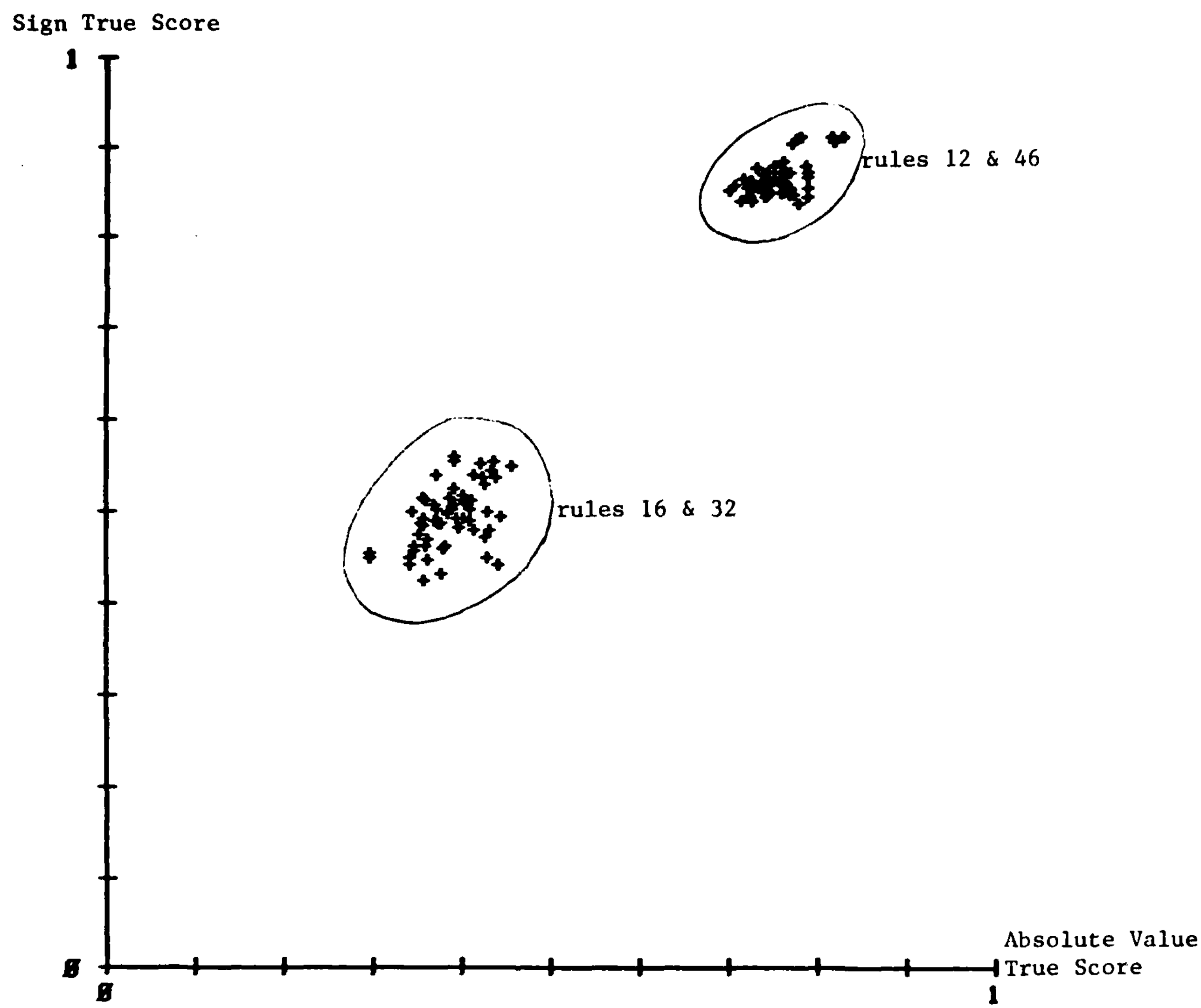

Figure 7: Plot of the Sign True Score Against Absolute Value for the Four Clusters Around Rules 12, 16, 32 and 46 in Figure 3.

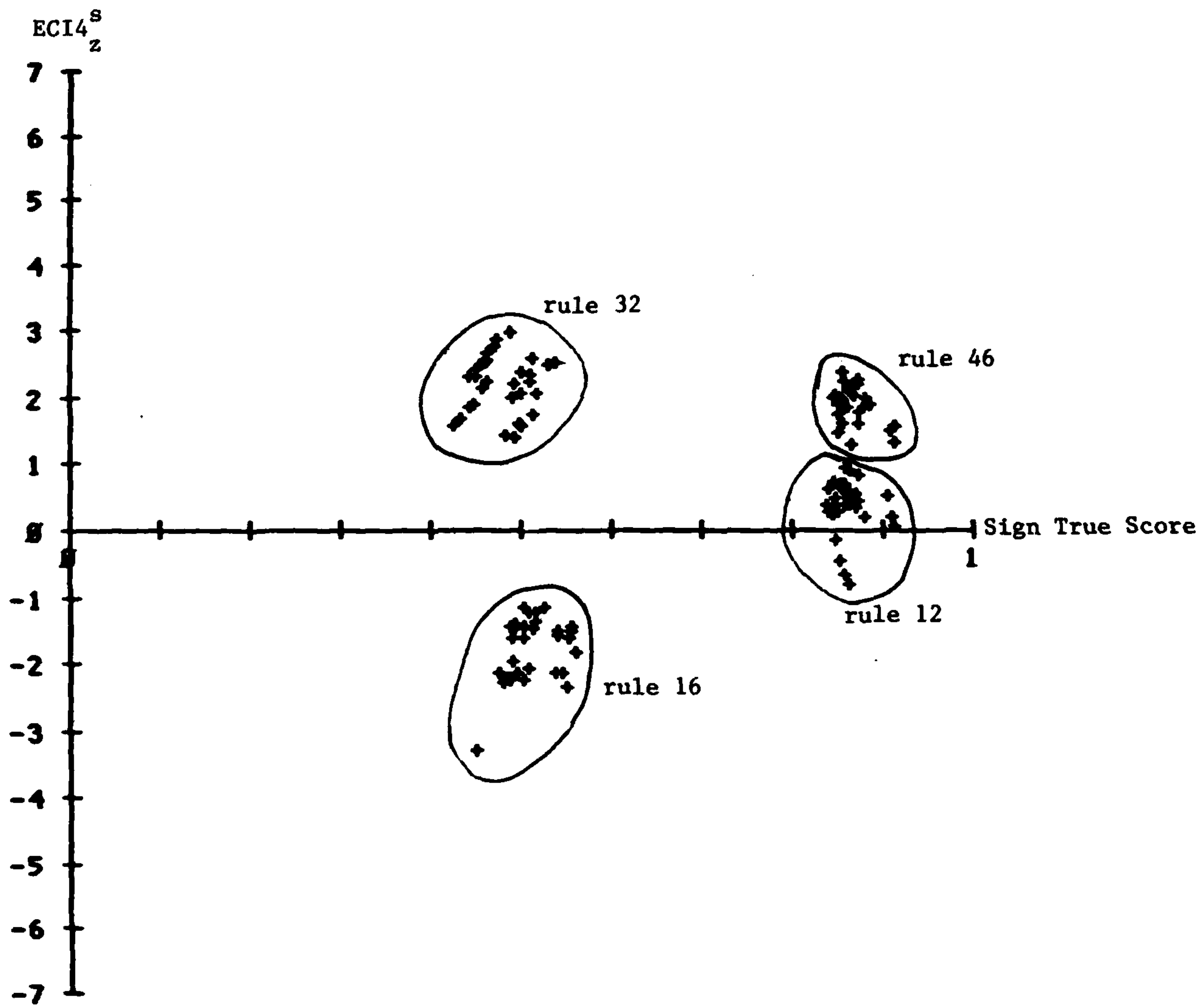

Figure 8: Plot of the Clusters Around Rules 12, 16, 32 and 46 in Figure 1, Sign True Score Against ECI^s .

Summary and Discussion

A probabilistic model for dealing with a variety of misconceptions is developed and its useful properties are demonstrated with a 40-item signed-number subtraction test. The model is tentatively named "rule space" into which all response patterns are mapped. Rule space is defined as a cartesian product of estimated true scores and the values of standardized extended caution index, $ECI4_z$ (Tatsuoka & Tatsuoka, 1982a). The advantage of using the standardized ECI is apparent from Figures 1, 2, 4 and 5 because ECI_z has the property of dispersing response patterns at the same fixed θ_i level. Therefore, if two response patterns from the same θ level are different, then their ECI_{iz}s have the two different values. As can be seen in Table 1, if we decompose the regular scoring into several components such as sign and absolute-value component scores in signed number arithmetic, then each rule has a much greater chance to be represented by a unique set of component response patterns. In the study of signed numbers, all erroneous rules discovered by SIGNBUG for over one thousand students have been uniquely represented so far by the two sets of response patterns. However, each subject matter may require a unique consideration of scoring procedures for the rule-space technique to be adapted. Then, by forming the rule spaces it may be possible to determine an individual student's state of knowledge by identifying a specific misconception, even when the responses are only partially consistent and cannot be diagnosed by the SIGNBUG approach.

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Appendices

Appendix I

Estimated $\hat{a}$s and $\hat{b}$s of the Sign Component Scores
(N = 172)

Items	$\hat{a}$s	$\hat{b}$s	Items	$\hat{a}$s	$\hat{b}$s
11	1.1499	-1.0980	33	1.1922	-.9672
2	.7023	-1.1965	34	1.2023	-.8493
4*			36	1.3678	-.9408
6	.8025	-2.1632	38	1.0887	-1.6538
7*			39	.3135	-4.9597
8	.8057	-2.0711	40	.6888	-1.9455
9	.7383	-2.0964	41	.6432	-2.2016
12	.4391	-2.3949	44	.8380	-1.8726
13*			45	1.2010	- 6620
16	1.1973	-.4075	48	.8798	-.4871
17	1.2428	-1.1168	49	1.3178	-.9092
18	.9571	-.8658	50	1.3102	-.8352
20	1.5489	-1.0717	52	1.5050	-.7836
22	.8465	-2.0972	54	.9070	-1.7964
23	.2113	-6.8217	55	.3192	-3.8657
24	.6632	-1.9173	56	.8360	-1.4982
25	.5425	-2.4858	57	1.3123	-1.4005
28	1.0400	-1.6857	60	.6391	-2.5071
29	1.3690	-.8293	61	1.6311	-.8136
32	1.0638	-.5307	64	.6505	-.5665

*The maximum likelihood procedure did not converge

Appendix II

Estimated $\hat{a}$s and $\hat{b}$s of Absolute Value Component Scores
(N = 172)

Items	$\hat{a}_a$	$\hat{b}_a$	Items	$\hat{a}_a$	$\hat{b}_a$
1	.2703	-4.8475	33	.5805	-2.1912
2	1.1097	-.8180	34	1.4556	-.4256
4	1.4449	-.5630	36	1.5291	-.4390
6	.9975	-.7687	38	2.6000	-.5729
7	.5672	-2.0084	39	.6082	-1.5998
8*			40	.4443	-2.6204
9	1.2718	-.4632	41	1.2948	-.5126
12	1.3016	-.5674	44	1.4394	-.6516
13	2.0761	-.6438	45	1.4138	-.6880
16	.5965	-1.7412	48	.4394	-1.7471
17	.5658	-1.9440	49	.4538	-2.3231
18	.9642	-.6542	50	1.7342	-.5412
20	1.4535	-.6188	52	2.0177	-.5074
22	2.6207	-.4121	54	1.6602	-.6386
23	.4755	-2.3936	55	.6428	-1.8268
24	.3909	-2.2248	56	.4285	-2.3563
25	2.1031	0.3970	57	1.4859	-.3948
28	1.4988	-.9005	60	1.5030	-.6680
29	1.9786	-.6244	61	1.5419	-.7219
32	.6542	-1.6818	64	.4339	-1.9638

*The maximum likelihood procedure did not converge

Distribution List

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Arlington, VA 22217

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Navy Personnel R&D Cent
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Great Lakes, IL 60088

1 Ted M. I. Yellen
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Navy Personnel R&D Center
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1 Library, Code P201L
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San Diego, CA 92152

6 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, DC 20390

1 Psychologist
ONR Branch Office
Bldg 114, Section D
666 Summer Street
Boston, MA 02210

1 Psychologist
ONR West
1030 East Green St.
Pasadena, CA 91106

1 Office of Naval Research
(442 PT)
800 N. Quincy Street
Arlington, VA 22217

5 Personnel & Training Research Programs
(442 PT)
Office of Naval Research
Arlington, VA 22217

1 Chief of Naval Operations
Res. Devel. & Studies Branch
(OP-115)
Washington, DC 20350

1 Lt. Frank C. Petho, MSC, USN, Ph.D.
Selection and Training Res. Div.
Human Performance Sciences Department
Naval Aerospace Med. Res. Lab.
Pensacola, FL 32508

1 Dr. Bernard Rimland (03B)
Navy Personnel R&D Center
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N-5
Naval Ed. & Training Command
NAS, Pensacola, FL 32508

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Training Analysis & Ev. Grp.
(TAEG)
Dept. of the Navy
Orlando, FL 32813

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Navy Personnel R&D Center
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Code 54 WZ
Dpt. of Admin. Sci.
U.S. Naval Postgrad. Schl.
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Navy Personnel R&D Center
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Navy Personnel R&D Center
San Diego, CA 92152

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Navy Personnel R&D Center
San Diego, CA 92152

Army

1 Technical Director
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 James Baker
Systems Manning Tech
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Beatrice Farr
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Myron Fischl
Army Res. Inst.
5001 Eisenhower Ave.
Aexandria, VA 22333

1 Dexter Fletcher
US Army Res. Inst.
5001 Eisenhwer Ave.
Alexandria, VA 22333

1 Dr. Michael Kaplan
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Milton S. Katz
Training Tech. Area
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Laurel Oliver
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Harold F. O'Neil, Jr.
Attn. PERI-OK
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Mr. Robert Ross
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

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Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Joseph Ward
Army Res. Inst.
5001 Eisenhower Ave.
Alexandria, VA 22333

Air Force

1 AF Human Resources Lab.
AFHRL/MPD
Brooks AFB, TX 78235

1 AF Office of Sci. Res.
Life Sciences Directorate, NL
Bolling AFB
Washington DC 20332

1 Dr. Earl A. Alluisi
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Brooks AFB, TX 78235

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling AFB,
Washington, DC 20332

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Res. Branch, AFMPC/MPCYPR
Randolph AFB, TX 78148

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HQ, Marine Corps
OTTI 31
Arlington Annex
Columbia Pike at Arlington Ridge Rd.
Arlington, VA 20380

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BCB, Bldg. 2009
Quantico, VA 22134

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1 Special Ast. for Marine Corps
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800 N. Quincy St.
Arlington, VA 22217

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HQ, Marine Corps
(Code MPI-20)
Washington DC 20380

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Coast Guard

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Coast Guard (G-P-1/2/TP42)
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1 Thomas A. Warm
Coast Guard Inst.
P.O. Substation 18
Oklahoma City, OK 73169

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Learning & Development
NIE
1200 19th St. NW
Washington, DC 20208

1 John Mays
National Inst. of Ed.
1200 19th St. NW
Washington, DC 20208

1 Richard McKillip
Personnel R&D Center
Personnel Management
1900 E. St. NW
Washington, DC 20415

1 William J. McLaurin
66610 Howie Court
Camp Springs, MD 20031

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National Inst. of Ed.
1200 19th St. NW
Washington, DC 20208

1 Dr. Andrew R. Molnar
Sci. Ed. Dev. & Res.
NSF
Washington, DC 20550

1 Dr. Joseph Psotka
NIE
1200 19th St. NW
Washington, DC 20208

1 Wallace Sinaiko
Program Director MRHS
Smithsonian Institution
801 N. Pitt Street
Alexandria, VA 22314

1 Dr. Vern W. Urry
Personnel R&D Center
Office of Personn. Mngmnt.
1900 E St. NW
Washington, DC 20415

1 Frank Withrow
US office of Ed.
400 Maryland Ave. SW
Washington, DC 20202

1 Dr. Joseph L. Young, Dir.
Memory & Cognitive Processes
NSF
Washington, DC 20550

Other Department of Defense

12 Defense Technical Information Center
Cameron Station, Bldg 5
Alexandria, VA 22314
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Testing Directorate
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Dept. of Statistics
Studiestraede 6
1455 Copenhagen
DENMARK

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Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Thomas Anderson
CSR
174 Children's Res. Lab.
51 Gerty Drive
Champaign, IL 61820

1 Dr. John Annett
Dept. of Psychology
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Coventry CV4 7AL
ENGLAND

1 1Psych. Res. Unit
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Campbell Park Offices
Canberra ACT 2600
AUSTRALIA

1 Dr. Allan Baddeley
Medical Res. Council
Applied Psych. Unit
15 Chaucer Road
Cambridge CB2 2EF
ENGLAND

1 Dr. Patricia Baggett
Dept. of Psych.
University of Colorado
Boulder, CO 80309

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Department of Computer Science
Stanford University
Stanford, CA 94305

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Educational Testing Serv.
Princeton, NJ 08450

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School of Ed.
Tel Aviv University
Ramat Aviv - Box 39040
Tel Aviv 69978
ISRAEL

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DezWPs im Streitkraefteamt
Postfach 20 50 03
D-5300 Bonn 2
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1 Dr. Darrel Bock
Dept. of Ed.
University of Chicago
Chicago, IL 60637

1 Liaison Scientists
Office of Naval Research
Branch Office, London
Box 39 FPO
New York, NY 09510

1 Dr. Lyle Bourne
Dept. of Psych.
University of Colorado
Boulder, CO 80309

1 Dr. Walter Bogan
4615 N. Park Ave, no. 1611
Chevy Chase, MD 20015

1 Dr. Robert Brennan
American College Testing Programs
P.O. Box 168
Iowa City, IA 52240

1 Dr. John S. Brown
XEROX Palo Alto Res. Cnt.
3333 Coyote Rd.
Palo Alto, CA 94304

1 Dr. C. Victor Bunderson
WICAT Inc.
University Plaza, Suite 10
1160 S. State St.
Orem, UT 84057

1 Dr. Leigh Burstein
Dept. of Education
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Los Angeles, CA 90024

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Psychometric Lab
Univ. of N. Carolina
Davie Hall 013A
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ronbach
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529-D Stinson
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Iowa City, IA 52240

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Montgomery College
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Univeraity of New England
Armidale, N. S. Wales 2351
AUSTRALIA

1 Dr. Edwin A. Fleishman
Advanced Research Resources Or.
Suite 900
4330 E. West Highway
Washington, DC 20014

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Bolt Beranek & Newman
50 Moulton St.
Cambridge, MA 02138

Dr. Paul Games
403D Carpenter
University Park, PA 16802

Dr. Robert Glaser
LRDC
University of Pittsburgh
3939 O'Hara St.
Pittsburgh, PA 15213

Dr. Bert Green
John Hopkins University
Dept. of Psychology
Charles & 34th St.
Baltimare, MD 21218

Dr. James Greeno
LRDC
3939 O'Hara St.
Pittsburgh, PA 15213

Dr. Ron Hambleton
School of Education
University of Massachusetts
Amherst, MA 01002

Dr. Delwyn Harnisch
ICBD
University of Illinois
51 Gerty Drive
Champaign, IL 61801

Dr. Chester Harris
School of Education
University of California
Santa Barbara, CA 93106

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The Rand Corporation
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Santa Monica, CA 90406

Dr. Frederick Hayes-Roth
The Rand Corporation
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Santa Monica, CA 90406

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Wicat, Inc.
Box 986
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Clark Kerr Hall
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CANADA

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Dept. of Psychology
University of Washington
Seattle, WA 98105

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2122 Coolidge St.
Lansing, MI 48906

1 Dr. Ed Hutchins
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Huynh Huynh
College of Education
University of South Carolina
Columbia, SC 29208

1 Professor John A. Keats
University of Newcastle
AUSTRALIA 2308

1 Jeff Kelety
Dept. of Instr. Tech.
University of S. Calif.
Los Angeles, CA 92007

1 Dr. Walter Kintsch
Dept. of Psych.
University of Colorado
Boulder, CO 80302

1 Dr. David Kieras
Dept. of Psych.
University of Arizona
Tucson, AZ 85721

1 Dr. Stephan Kosslyn
Harvard University
Dpt. of Psych.
33 Kirkland St.
Cambridge, MA 02138

1 Mr. Marlin Kroger
1117 Via Goleta
Palos Verdes Estates, CA 90274

1 Dr. Marcy Lansman
Dpt. of Psych. NI 25
Univ. of Washington
Seattle, WA 98195

1 Dr. Jill Larkin
Dpt. of Psych.
Carnegie Mellon Univ.
Pittsburgh, PA 15213

1 Dr. Alan Lesgold
LRDC
Univ. of Pittsburgh
Pittsburgh, PA 15260

1 Dr. Michael Levine
Dept. of Ed Psych
210 Education Bldg.
University of Illinois
Champaign, IL 61801

1 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat 23
9712GC Groningen
NETHERLANDS

1 Dr. Robert Linn
210 Education
University of Illinois
Urbana, IL 61801

1 Bob Loo, Ph.D.
Department of Psychology
The University of Calgary
2920 - 24th Ave. NW
Calgary, Alberta
CANADA T2N 1N4

1 Dr. Frederick M. Lord
Educational Testing Ser.
Princeton, NJ 08540

1 Dr. Drew Malizio
American Counc. on Ed.
No. 1 Pont Circle, #20
Washington, DC 20036

1 Dr. Gary Marco
Educational Testing Service
Princeton, NJ 08540

1 Dr. Scott Maxwell
Dpt. of Psych.
Univ. of Houston
Houston, TX 77004

1 Dr. David McArthur
CSE 145 Moor Hall
UCLA
Los Angeles, CA 90024

1 Dr. Samuel T. Mayo
Loyola U. of Chicago
820 N. Michigan Av.
Chicago, IL 60611

1 Dr. Erik McWilliams
Science Ed. Dev. & Res.
National Science Foundation
Washington, DC 20550

1 Dr. Peter Mich
Ed Psych
Enderis Hall 719
University of Wisconsin
P.O. Box 413
Milwaukee, WE 53201

1 Dr. David Miller
Graduate School of Ed.
UCLA
Los Angeles, CA 90024

1 Dr. Mark Miller
TI Computer Sci. Lab
C/O 2824 Winterplace Circle
Plano, TX 75075

1 Dr. Allen Munro
Behvr. Tech. Lab.
1845 Elena Ave. 4th floor
Redondo Beach, CA 90277

1 Dr. Anthony J. Nitko
School of Ed.
Division of Ed. Studies
University of Pittsburgh
5C03 Forbes Quandrangle
Pittsburgh, PA 15260

1 Dr. Donald A. Norman
Dpt. of Psych. C-009
Univ. of Calif.
La Jolla, CA 92093

1 Dr. Melvin Novick
356 Lindquist Cntr for Measur.
University of Iowa
Iowa City, IA 52242

1 Dr. Jesse Orlansky
Inst. for Defense Analyses
400 Army Navy Drive
Arlington, VA 22202

1 Dr. Seymour A. Papert
MIT
Artific. Intelli. Lab.
545 Technology Square
Cambridge, MA 02139

1 Wayne M. Patience
American Council on Education
GED Testing Service, suite 20
One Dupont Circle, NW
Washington, DC 20036

1 Dr. James A. Paulson
Portland State University
P.O. Box 751
Portland, OR 97207

1 Dr. James Pellegrino
Univ. of Calif.
Dpt. of Psych.
Santa Barbara, CA 93106

1 Mr. Luigi Petrullo
2431 N. Edgewood St.
Arlington, VA 22207

1 Dr. Martha Polson
Dpt. of Psych.
Campus Box 346
University of Colorado
Boulder, CO 80309

1 Dr. Peter Posner
Dpt. of Psych.
Univ. of Oregon
Eugene, OR 97403

1 Dr. Peter Polson
Dpt. of Psych.
University of Colorado
Boulder, CO 80309

1 Dr. Diane M. Ramsey-Klee
R-K Res. & System Design
3947 Ridgemont Dr.
Malibu, CA 90265

1 Minrat M. L. Rauch
P II 4
Bundesministerium der
Verteidigung
Postfach 1328
D-53 Bonn 1
GERMANY

1 Dr. Mark D. Reckase
Ed Psych Dept.
University of Missouri
4 Hill Hall
Columbia, MO 65211

1 Dr. Lauren Resnick
LRDC
University of Pittsburgh
3939 O'Hara St.
Pittsburgh, PA 15213

1 Dr. Mary Riley
LRDC
Univ. of Pittsburgh
3939 O'Hara St.
Pittsburgh, PA 15213

1 Dr. Andrew M. Rose
American Inst. for Res.
1055 Thomas Jefferson St. NW
Washington, DC 20007

1 Dr. Leonard L. Rosenbuam
Dept. of Psychology
Montgomery College
Rockville, MD 20850

1 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Ave.
Murry Hill, NJ 07974

1 Dr. Lawrence Rudner
403 Elm Ave.
Takoma Park, MD 20012

1 Dr. David Rumelhart
Cntr. for Human Info.
Univ. of Calif.
La Jolla, CA 92093

1 Dr. J. Ryan
Dept. of Ed.
University of S. Carolina
Columbia, SC 29208

1 Dr. Fumiko Samejima
Dept. of Psychology
U. of Tennessee
Knoxville, TN 37916

1 Dr. Alan Schoenfeld
Dpt. of Mathematics
Hamilton College
Clinton, NY 13323

1 Dr. Robert J. Seidel
Instr. Tech. Group
HUMMRRO
300 N. Washington St.
Alexandria, VA 22314

1 Dr. John Serber
University of Wisconsin
Dept. of Ed Psych
Milwaukee, WI 53201

1 Dr. Shigemasu
University of Tohoku
Dept. of Ed Psych
Kawauchi, Sendai 980
JAPAN

1 Dr. Edwin Shirkey
Dept. of Psychology
University of Centl Florida
Orlando, FL 32816

1 Dr. Ed Smith
Bolt Beranek & Newman, Inc.
50 Moulton St.
Cambridge, MA 02138

1 Dr. Richard Snow
School of Ed.
Stanford University
Stanford, CA 94305

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 Dr. Albert Stevens
Bolt Beranek & Newman, Inc.
50 Moulton St.
Cambridge, MA 02138

1 Dr. David E. Stone
Hazeltine Corp.
7680 Old Springhouse Rd.
McLean, VA 22102

1 Dr. Patrick Suppes
Inst. for Math. Studies
in Soc. Sci.
Stanford University
Stanford, CA 94305

1 Dr. Hariharan Swaminathan
Lab. of Psychom. & Evl. Res.
School of Ed.
University of Massachusetts
Amherst, MA 01003

1 Dr. Brad Sympson
Psychometric Research Group
Ed. Testing Service
Princeton, NJ 08541

n /

Dr. David Thissen
Dept. of Psychology
U. of Kansas
Lawrence, KS 66044

Dr. John Thomas
IBM Thmas Watson
Res. Cnt.
P.O. Box 218
Yorktown Heighs, NY 10598

Dr. Perry Thorndyke
The Rand Corp.
1700 Main St.
Santa Monica, CA 90406

Dr. Robert Tsutakawa
Dept. of Statistics
University of Missouri
Columbia, MO 65201

Dr. Howard Wainer
Division of Psychological Studies
Ed. Testing Service
Princeton, NJ 08540

Dr. Keith Wescourt
Information Sciences Dpt.
The Rand Corp.
1700 Main St.
Santa Monica, CA 90406

1 P.O. White
Dept. of Psychology
Institute of Psychiatry
DeCrespigry Park
London SE5 8AF
ENGLAND

1 Dr. Susan Whitely
Psychology Dept.
University of Kansas
Lawrence, KS 66044

1 Wolfgang Wildgrube
Streitdraefteamt
Box 20 50 03
D-5300 Bonn 2
WEST GERMANY

1 Dr. Steven Wise
Dept. of Guid. & Ed Psych
S. Illinis University
Carbondale, IL 62901