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STANDARDIZED EXTENDED CAUTION INDICES
AND
COMPARISONS OF THEIR RULE DETECTION RATES

KIKUMI K. TATSUOKA
MAURICE M. TATSUOKA

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Kikumi K. Tatsuoka
252 ERL
103 S. Mathews
University of Illinois
Urbana, IL 61801
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**ABSTRACT (Continue on reverse side if necessary and identify by block number)**

Several extended caution indices (ECIs) have been introduced earlier as a link between two distinctly different approaches: One based on the standard statistics and the other, a model-based approach utilizing item response theory (IRT). Expected values and variances of some ECIs are derived and their statistical properties are compared.
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Abstract

Several extended caution indices (ECIs) have been introduced earlier as a link between two distinctly different approaches: one based on standard statistics and the other, a model-based approach utilizing item response theory (IRT). Expected values and variances of some ECIs are derived and their statistical properties are compared and discussed. Then, standardized ECIs are introduced and their distributions are investigated. It turns out that the standardized ECIs fit normal distributions well. A comparison of detection rates among appropriateness measures based on IRT theory is carried out with the signed-number dataset. There is no noticeable difference in their detection rates using the 80% intervals.
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Introduction

An increasing number of researchers have begun to show interest in using response patterns of n items for analyzing performance on test scores. By so doing, more information is obtainable than by using only traditional total scores. Tatsuoka and her colleagues (Birenbaum & Tatsuoka, 1982a, b; Tatsuoka & Tatsuoka, 1982a) have demonstrated that some wrong rules of arithmetic computations (fractions and signed-numbers) can produce the right score of 1 on as much as 60% of the test items. If many students apply a variety of wrong rules consistently throughout the test, then these faulty rules cause a serious problem by violating the unidimensionality assumption of a dataset. After rescoring these correct responses obtained by faulty rules, the dataset became nearly unidimensional. They have developed several indices to detect aberrant response patterns resulting from consistent application of wrong rules (Tatsuoka & Tatsuoka, 1982b) and have shown one of them, the individual consistency index (ICI), to spot more than 90% of such aberrant response patterns (Tatsuoka & Tatsuoka, 1981).

Rudner (1982) investigated the detection rates of various personal indices (norm conformity index, caution index, personal biserial and appropriateness measures based on item response theory) and found that the indices based on IRT are more efficient for detecting anomalous response patterns than those based on observed item response and summary statistics. However, estimating parameters of IRT models requires a substantial number of subjects while it is often impossible to have such a large sample size in many classroom settings.
Sato (1975) developed the caution index in conjunction with S-P curve theory and successfully used it for diagnosing students' performance and evaluating instructional materials in Japan. Harnisch and Linn (1981) demonstrated its usefulness by applying it to a NAEP dataset (National Assessment of Educational Progress). Although their analysis is based on a large dataset, their results show clearly that analysis of response patterns as a whole provides very useful information associated with individual differences, curriculum differences and school differences.

The concepts of S-P curve theory and caution index have been extended to the continuous domain of IRT models from the approach based on the discrete summary statistics by Tatsuoka and Linn (1982). They have developed five alternative indices and named them extended caution indices 1, 2, 3, 4 and 5. In this paper, further statistical properties of ECI1, 2, and 4 will be discussed and their detection rates will be compared.

Statistical Properties of Extended Caution Indices

Definition of the Extended Caution Indices

A group of extended caution indices (ECI) has been introduced as a link between two distinct approaches of detecting aberrant response patterns (Tatsuoka & Linn, 1981). One is based on the use of binary response patterns and their standard summary statistics (Sato, 1975; van der Flier, 1977; Tatsuoka & Tatsuoka, 1980, 1982a), while the other is a model-based approach. In the latter, the patterns of probabilities that are derived from item response theory are utilized in calculating appropriateness measures together with observed binary response patterns.
ECIs are an extension of Sato's caution index to the approach used in IRT. In this section, three of the five ECIs will be investigated in terms of their expected values, variances, and advantages and disadvantages.

Let $y_{ij}$ for $i=1,...,N; j=1,...,n$ be the binary score of subject $i$ to item $j$, $y_i$ be the $i$th row sum, and $y_j$ the $j$th column sum of the data matrix $(y_{ij})$. Let $P_{ij}$ be the probability of subject $i$ answering item $j$ correctly, which may be based on the one-, two- or three-parameter logistic model. That is,

$$P_{ij} = c_j + \frac{1 - c_j}{1 + \exp[-a_j (\theta_i - b_j)]}$$

where $c_j = 0$ and $a_j = 1$ for the one-parameter logistic model; $c_j = 0$ for the two-parameter logistic model. Thus, two data matrices -- one comprising observed binary scores of $n$ items for $N$ subjects ($y_{ij}$) and the other consisting of ($P_{ij}$) -- may be introduced. We refer to ($y_{ij}$) as the observed binary matrix and ($P_{ij}$) as the probability matrix.

Let $G_j$ be the $j$th element of a vector approximating the group response curve (GRC) for item $j$, and $T_i$ be that of the vector for the test response curve (TRC) for subject $i$. Then

$$G_j = \frac{1}{N} \sum_{i=1}^{N} P_{ij}$$

$$T_i = \frac{1}{n} \sum_{j=1}^{n} P_{ij}$$

In other words, $G_j$ for item $j$ and $T_i$ for subject $i$ are the $j$th column sum and the $i$th row sum, respectively, of the probability matrix ($P_{ij}$).

Three of the five ECIs are defined as complements of the ratio of two covariances between various pairs of row vectors taken from the two matrices.
\[
\text{ECI}_{1i} = 1 - \frac{\text{cov}(y_i, \bar{y})}{\text{cov}(\bar{p}_i, \bar{y})} \quad (1)
\]
\[
\text{ECI}_{2i} = 1 - \frac{\text{cov}(\bar{y}, \overline{G})}{\text{cov}(G, \bar{p}_i)} \quad (2)
\]
\[
\text{ECI}_{3i} = 1 - \frac{\text{cov}(\bar{y}, \overline{p_i})}{\text{cov}(G, \bar{p}_i)} \quad (3)
\]

where \(y_i = (y_{i1}, y_{i2}, \ldots, y_{in})\), the vector of binary scores for subject \(i\) or the \(i\)th row vector,  

\(\bar{y} = (y_1, y_2, \ldots, y_n)\), the column-sum vector in the observed binary matrix,  

\(\bar{p}_i = (p_{i1}, p_{i2}, \ldots, p_{in})\), the probability vector from the \(i\)th row in the probability matrix, and  

\(G = (G_1, G_2, \ldots, G_n)\), the GRC vector which is the column-sum vector of \((p_{ij})\). Expression (1) is defined by forming the ratio of the following covariances: the numerator is the covariance of subject \(i\)'s response pattern and the column-sum vector over \(n\) items in \((y_{ij})\), and the denominator is the covariance of the \(i\)th row probability vector derived from a logistic model and the column-sum vector in \((y_{ij})\). Expressions (2) and (3) have the same denominator, the covariance of the GRC vector and the \(i\)th probability vector, and the numerators are covariances of the response pattern vector with the GRC vector and the probability vector, respectively.

When \(y_i\) consists of all 1s or 0s, the second terms of the ECI\(s\) become undetermined.
The expectations of EC11, EC12, and EC14

In this section, the expectations and variances of the three ECIs given by Equations (1), (2) and (3) will be derived. The actual values of the ECIs for subject i can be calculated by replacing the item and person parameters with their estimated values ̂a_j, ̂b_j and ̂θ_i based on the maximum likelihood method. It is known that the maximum likelihood estimates of item and person parameters satisfy the likelihood conditions (Lord and Novick, 1968) given in Equations (4).

\[
\sum_{j=1}^{n} \hat{a}_j \hat{y}_{ij} = \sum_{j=1}^{n} \hat{b}_j \hat{y}_{ij} = \sum_{j=1}^{n} \hat{y}_{ij} = \sum_{j=1}^{n} \sum_{j=1}^{n} g_{ij} y_{ij} \]

Since the ECIs are functions of the person parameter θ_i, the conditional expected values and variances of the ECIs for a fixed ability level will be introduced. Hereafter, the circumflex on ̂P_{ij} (and its ith-row vector ̂P_i) will be omitted to simplify the notation.

EC11

The conditional expectation of the first ECI defined in Equation (1) is given by the following:

\[
E(\text{ECI}\,|\,\theta_i) = 1 - E \left( \frac{\text{cov}(y_k, y_j)}{\text{cov}(\hat{P}_i, y_j)} \,|\, \theta_i \right)
\]

\[
= 1 - \frac{E[\text{cov}(y_k, y_j|\theta_i)]}{\text{cov}(\hat{P}_i, y_j)}
\]

(5)
The observed vector $y_k$ is a random vector at the level $\theta_1$ and the expectation is obtained over $k$. Now, we have to find the expectation in the numerator of the second fraction, $E[\text{cov}(y_k, y_\cdot)\mid \theta_1]$. First, the covariance of $y_k$ and $y_\cdot$ is rewritten as the summation of the product of the deviations:

$$E[\text{cov}(y_k, y_\cdot)\mid \theta_1] = E\left[\frac{1}{n} \sum_{j=1}^{N} (y_{kj} - p_{kj})(y_\cdot j - p_\cdot j)\mid \theta_1\right] / n$$

where $p_{kj}$ is the $i$:th row mean of $(y_{ij})$ and $p_\cdot j$ is the mean of the row means or column means as follows,

$$p_\cdot j = \frac{1}{n} \sum_{j=1}^{N} p_{kj} = \frac{1}{N} \sum_{i=1}^{n} p_{kj}.$$ 

By using the second members of Equations (4), this expectation reduces to the covariance of $P_{kj}$ and $y_\cdot$. Thus, the conditional expectation of $ECI_1$ at the fixed level $i$ becomes zero, as summarized in Equation (6).

$$E(ECI_1\mid \theta_1) = 1 - \frac{\text{cov}(P_{kj}, y_\cdot)}{\text{cov}(P_{kj}, y_\cdot)} \equiv 0.$$  (6)

The conditional variance of $ECI_1$ at the fixed level $i$ is

$$\text{Var}(ECI_1\mid \theta_1) = E(ECI_1 - E(ECI_1\mid \theta_1))^2.$$  (7)

By substituting the result from (6), the conditional variance (7) becomes $E(ECI_1^2\mid \theta_1)$. That is:

$$E(ECI_1^2\mid \theta_1) = E\left(\left[1 - \frac{\text{cov}(y_k, y_\cdot)}{\text{cov}(P_{kj}, y_\cdot)}\right]^2\mid \theta_1\right)$$

$$= -1 + \frac{E[\text{cov}^2(y_k, y_\cdot)\mid \theta_1]}{\text{cov}^2(P_{kj}, y_\cdot)}$$  (8)

where we have again used the fact that $E[\text{cov}(y_k, y_\cdot)] = \text{cov}(P_{kj}, y_\cdot)$. The numerator of the last term of Equation (8), however, can be expanded
to the sum of the diagonal and off-diagonal terms, and then by applying
the conditions given in Equations (4), we obtain Equation (9).

$$
\frac{1}{n^2} E\left[ \sum_{j=1}^{n} (y_{kj} - P_{1.})(y_{j} - P_{..}) \right]^2 \left[ \theta_1 \right]
$$

$$
= \frac{1}{n^2} E\left[ \sum_{j=1}^{n} (y_{kj} - P_{1.})^2(y_{j} - P_{..})^2 \left[ \theta_1 \right] \right]
$$

$$
+ \frac{1}{n^2} E(\sum_{j \neq h} (y_{kj} - P_{1.})(y_{kh} - P_{1.})(y_{j} - P_{..})(y_{h} - P_{..}) \left[ \theta_1 \right])
$$

(9)

The first term, the diagonal part inside the parentheses of the above
equation, is:

$$
E\left[ \sum_{j=1}^{n} (y_{kj} - P_{1.})^2(y_{j} - P_{..})^2 \left[ \theta_1 \right] \right]
$$

$$
= \sum_{j=1}^{n} (y_{j} - P_{..})^2 E\left[ (y_{kj} - P_{1.})^2 \left[ \theta_1 \right] \right]
$$

$$
= \sum_{j=1}^{n} (y_{j} - P_{..})^2[P_{ij}(1 - P_{ij}) + (P_{ij} - T_i)^2]
$$

The second term inside the parenthesis is:

$$
E\left( \sum_{j \neq h} (y_{kj} - P_{1.})(y_{kh} - P_{1.})(y_{j} - P_{..})(y_{h} - P_{..}) \left[ \theta_1 \right] \right)
$$

$$
= \sum_{j \neq h} (y_{j} - P_{..})(y_{h} - P_{..})(P_{ij} - T_i)(P_{ih} - T_i)
$$

Adding the results of the two expectations gives Equation (10).

$$
\frac{1}{n^2} E\left[ \sum_{j=1}^{n} (y_{kj} - P_{1.})(y_{j} - P_{..}) \right]^2 \left[ \theta_1 \right]
$$

$$
= \frac{1}{n^2} \left[ \sum_{j=1}^{n} (y_{j} - P_{..})(P_{ij} - T_i) \right]^2 + \frac{1}{n^2} \left[ \sum_{j=1}^{n} (y_{j} - P_{..})^2P_{ij}(1 - P_{ij}) \right]
$$

$$
= \text{cov}^2(y_{..}, P_{1.}) + \frac{1}{n^2} \sum_{j=1}^{n} (y_{j} - P_{..})^2 \sigma_{ij}^2
$$

(10)
Substituting (10) in Equation (8), the variance of ECI becomes:

\[
\text{Var}(ECI) = -1 + \frac{\text{cov}^2(y, P_i) + \sum_{j=1}^{n} \sigma^2_{ij} (y_j - \mu_j)^2 / n^2}{\text{cov}^2(P_i, y)}
\]

\[
= \frac{\sum_{j=1}^{n} \sigma^2_{ij} (y_j - \mu_j)^2}{n^2 \text{cov}^2(P_i, y)}
\]

\[(11)\]

ECI2

The conditional expectation of the second ECI is given by

\[
E(ECI_2|\theta_1) = 1 - E\left[\frac{\text{cov}(y_k, G)}{\text{cov}(G, P_i)}|\theta_1\right]
\]

\[
= 1 - \frac{E[\text{cov}(y_k, G)|\theta_1]}{\text{cov}(G, P_i)}
\]

\[(12)\]

But

\[
E[\text{cov}(y_k, G)|\theta_1] = \frac{1}{n} \sum_{j=1}^{n} E[\frac{1}{n} (y_{kj} - P_i)(G_j - T)|\theta_1]
\]

\[
= \frac{1}{n^2} \sum_{j=1}^{n} E[(y_{kj} - P_i)(G_j - T)|\theta_1]
\]

\[
= \frac{1}{n^2} \sum_{j=1}^{n} (P_i G_j - T)(G_j - T) = \text{cov}(P_i, G),
\]

where

\[
T = \frac{\sum_{i=1}^{N} T_i}{N} = \frac{\sum_{j=1}^{n} G_j}{n}
\]

By substituting this result in Equation (12), we get (13).

\[
E(ECI_2|\theta_1) = 1 - \frac{\text{cov}(P_i, G)}{\text{cov}(G, P_i)} = 0
\]

\[(13)\]
The conditional variance of \( ECI_2 \) is given by Equation (14),

\[
\text{Var}(ECI_2|\theta_1) = E[(ECI_2 - E(ECI_2)|\theta_1)^2|\theta_1) = E(ECI_2^2|\theta_1)
\]

\[
= -1 + \frac{E[\text{cov}^2(y_k, G)|\theta_1]}{\text{cov}^2(G, P_i)}
\]

Equation (14)

The expectation of the squared covariance of \( y_k \) and \( G \) can be simplified and given by Equation (15).

\[
E[\text{cov}^2(y_k, G)|\theta_1] = \text{cov}^2(P_i, G) + \frac{1}{n^2} \sum_{j=1}^{n} \sigma_{ij}^2 (G_j - T)^2
\]

Equation (15)

By substituting (15) in (14), we get (16).

\[
\text{Var}(ECI_2|\theta_1) = \frac{\sum_{j=1}^{n} (G - T)^2 \sigma_{ij}^2}{n^2 \text{cov}^2(G, P_i)}
\]

Equation (16)

\( ECI_4 \)

The conditional expectation of \( ECI_4 \) is

\[
E(ECI_4|\theta_1) = 1 - E[\frac{\text{cov}(y_k, P_i)|\theta_1}{\text{cov}(G, P_i)}]
\]

Equation (17)

where \( y_k \) is a random variable from the distribution of binary responses to \( n \) items at the fixed ability level \( i \). Since the denominator of the expected value, \( \text{cov}(G, P_i) \), is fixed at level \( i \), the second term will be simply the expectation of the numerator divided by the covariance of \( G \) and \( P_i \), \( E[\text{cov}(y_k, P_i)|\theta_1]/\text{cov}(G, P_i) \).
But \( E(y_{kj} - p_i, \theta_1) = P_{ij} - T_1 \) because of Equations (4)

Therefore,

\[
E(ECI4|\theta_1) = \Phi_1 - \frac{\text{cov}(p_i, p_j)}{\text{cov}(G, p_j)}
\]

\[
= 1 - \frac{\text{Var}(p_i)}{\text{cov}(G, p_j)}
\]

(18)

The conditional variance of ECI4 is given by Equations (19).

\[
\text{Var}(ECI4|\theta_1) = E[(ECI4 - E(ECI4))^2|\theta_1]
\]

(19)

Substituting the expectation of ECI4 from Equation (18), (19) becomes

\[
\text{Var}(ECI4|\theta_1) = E\left[ \frac{\text{cov}(p_i, p_j)}{\text{cov}(G, p_j)} - \frac{\text{cov}(y_k, p_i)}{\text{cov}(G, p_j)} \right]^2|\theta_1
\]

A straightforward expansion of the inside of the parentheses leads to Equation (20).

\[
\text{Var}(ECI4|\theta_1) = \frac{E[\text{cov}^2(y_k, p_i)|\theta_1]}{\text{cov}^2(G, p_j)} - \frac{\text{cov}^2(p_i, p_j)}{\text{cov}^2(G, p_j)}
\]

(20)

The numerator of the first term, \( E[\text{cov}^2(y_k, p_i)|\theta_1] \), can be simplified in the same manner as in the case of ECI1.

\[
E[\text{cov}^2(y_k, p_i)|\theta_1]
\]

\[
= \frac{1}{n^2} E[\sum_{j=1}^{n}(y_{kj} - p_{i,})(p_{ij} - T_1)]^2|\theta_1
\]

\[
= \frac{1}{n^2} E[\sum_{j=1}^{n}(y_{kj} - p_{i,})^2(p_{ij} - T_1)^2|\theta_1
\]

\[
+ \frac{1}{n^2} E[\sum_{j\neq h}(y_{kj} - p_{i,})(y_{kh} - p_{i,})(p_{ij} - T_1)(p_{ih} - T_1)|\theta_1]
\]

10
Because of local independence and Equation (4), we obtain the following two relations:

\[ E \left[ \sum_{j=1}^{n} (y_{kj} - P_{i.})^2 (P_{ij} - T_{i})^2 \right] = \sum_{j=1}^{n} \left( \sigma_{ij}^2 + (P_{ij} - T_{i})^2 \right) (P_{ij} - T_{i})^2 \]

and

\[ E \left[ \sum_{j \neq h} (y_{kj} - P_{i.})(y_{kh} - P_{h.})(P_{ij} - T_{i})(P_{ih} - T_{i}) \right] = \sum_{j \neq h} (P_{ij} - T_{i})^2 (P_{ih} - T_{i})^2 | \theta_1 \]

By adding the results, we obtain

\[ E[\text{cov}^2(y_k, P_\ell) | \theta_1] \]

\[ = \frac{1}{n^2} \sum_{j=1}^{n} (P_{ij} - T_{i})^2 \left( \frac{1}{n^2} \sum_{j=1}^{n} \sigma_{ij}^2 (P_{ij} - T_{i})^2 \right) \]

\[ = \text{Var}^2(P_{ij}) + \frac{1}{n^2} \sum_{j=1}^{n} \sigma_{ij}^2 (P_{ij} - T_{i})^2 \quad (21) \]

By substituting (21) in (20), we get Equation (22), the variance of ECI4.

\[ \text{Var} (ECI4 | \theta_1) = \frac{\text{cov}^2(P_{i}, P_{ij}) + \frac{1}{n^2} \sum_{j=1}^{n} \sigma_{ij}^2 (P_{ij} - T_{i})^2}{\text{cov}^2(G, P_{i})} - \frac{\text{cov}^2(P_{i}, P_{ij})}{\text{cov}^2(G, P_{i})} \]

\[ = \frac{\Sigma \sigma_{ij}^2 (P_{ij} - T_{i})^2}{n^2 \text{cov}^2(G, P_{i})} \quad (22) \]
Comparison of Some Statistical Properties of the Three Indices

ECI1, ECI2, and ECI4

Comparison of the Standard Errors

The conditional expectations of the three indices are different in a manner that suggests that ECI1 and ECI2 are similar to each other, while ECI4 stands alone. ECI1 and ECI2 have the constant expectation zero, regardless of the level of person parameter θ_i. On the other hand, the expectation of ECI4 is a function of θ_i, as shown in Figure 1 for the dataset obtained from a 32-item signed-number subtraction test. The x-axis represents true scores and the y-axis the 127 students' expected ECI4 values. The curve in Figure 1 decreases monotonically as the true score decreases. The standard error of ECI4 is the square root of expression (22) and is also a function of θ. Figure 2 shows the relationship between the standard error and the true scores. (The estimated true score of IRT was used instead of θ_i so as to have a value between 0 and 1, which facilitates comparison across different tests.)

For students whose true scores are extremely high or low, the standard-error curve rises sharply, while for average scores, it becomes rather flat.

Figures 3 and 4 are plots of the standard errors [square roots of expression (11) and (16)] of ECI1 and ECI2 against true score as the x-axis. They are almost identical curves that are nearly horizontal for the average true scores but increase rather rapidly at both the high and low extremes of true scores.
FIGURE 1: Expectation of ECI4 Plotted Against the True Score
FIGURE 2: The Standard Error of ECI4 Plotted Against the True Score
ECI1 and ECI2 correlate highly ($r = .97$, see Appendix XI) and have the same constant expectation of zero. Moreover, their standard errors have almost identical curves when plotted against true scores, so we will drop ECI1 hereafter and make comparisons between ECI2 and ECI4. Since ECI2 is defined by using the elements in the probability matrix ($P_{ij}$), the investigation of ECI2 and ECI4 will be more interesting.

Standardized Extended Caution Indices, $ECI_{2z}$ and $ECI_{4z}$ and their Density Functions

ECIs can be standardized by subtracting their expected values and then dividing it by their standard errors. Equations (23) and (24) are the standardized extended caution indices $ECI_{2}$ and $ECI_{4}$.

$$ECI_{2z} = \frac{ECI_{2} - E(ECI_{2} | \theta_{i})}{SE(ECI_{2} | \theta_{i})} = \frac{ncov(P_{i} - \bar{y}_{i}, \bar{G})}{\sqrt{\sum_{j=1}^{n} \sigma_{ij}^2 (P_{ij} - T)^2}}$$

$$ECI_{4z} = \frac{ECI_{4} - E(ECI_{4} | \theta_{i})}{SE(ECI_{4} | \theta_{i})} = \frac{ncov(P_{i} - \bar{y}_{i}, \bar{P}_{i})}{\sqrt{\sum_{j=1}^{n} \sigma_{ij}^2 (P_{ij} - T_{i})^2}}$$

As can be seen in Equations (23) and (24), the second variables of the covariances in the numerators are $\bar{G}$ and $\bar{P}_{i}$, respectively. The denominator for $ECI_{2z}$ involves the group-oriented vector $\bar{G} - T_{i}$ while that for $ECI_{4z}$ involves the individual-oriented vector at the level $i$, $\bar{P}_{i} - T_{il}$. Tatsuoka and Linn (1982) argue that $ECI_{4}$ may correspond to the individual consistency index (ICI) introduced in Tatsuoka & Tatsuoka (1980, 1982a) while $ECI_{2}$ may function similarly to the group dependent
FIGURE 3: The Standard Error of ECI1 Plotted Against the True Score
FIGURE 4: The Standard Error of EC12 Plotted Against the True Score
indices, i.e., Sato's caution index (1975) or the norm conformity index (Tatsuoka & Tatsuoka, 1980, 1982a). The ICI has proven to be effective in spotting the aberrant response patterns resulting from consistent application of erroneous rules of operation (Tatsuoka & Tatsuoka, 1981). Our prediction with regard to detection rates of erroneous rules of operation is that ECI4 should be better than ECI2.

It should be noted that the scale of the original ECIs are functions of $\theta$ but those of the standardized ECIs no longer depend on $\theta$. As a result, two ECI4z (or ECI2z) values obtained from different $\theta$ levels are comparable in terms of the extent of anomaly they signify. However, the density functions of ECI2z and ECI4z have to be investigated in order to determine their differences statistically.

Figures 5 and 6 show the goodness-of-fit test of the normal distribution for ECI2z and ECI4z. Appendices I and II give the tests of the normal distribution for ECI1z and 1z (Levine & Drasgow's standardized appropriateness measure, 1982), while Appendices III, IV and V give the goodness-of-fit tests of beta distributions for ECI1z, ECI2z, and ECI4z. The data used in these figures are based on 2,400 students' scores obtained from a math test (National Assessment of Educational Progress series, mathematics for 13 year olds, Booklet 4). As can be seen in the figures, both the standardized ECIs fit normal distributions well. Similar results are obtained from the NAEP data, Booklet 5.

Appendices VII, VIII, IX and X give the standard errors of ECI1z, ECI2z, and ECI4z and the expectation of ECI4z, obtained from the NAEP data. Although the NAEP data is used for testing "goodness of fit" of the ECIs with theoretical distributions, we will go back to the signed
FIGURE 5: Goodness of Fit Test for the Normal Distribution:
The Stepfunction is a Cumulative Distribution of EC14:
The Smooth Curve is a Theoretical Curve
FIGURE 6: Goodness of Fit Test for the Normal Distribution:
The Stepfunction is the Cumulative Distribution of ECI2 z
number data in order to investigate the detection rate of aberrant response patterns by the standardized ECIs. In the next section, a brief description of the dataset and procedure for the comparisons will be described.

A brief description of the dataset

Birenbaum and Tatsuoka (1982a) have demonstrated that the traditional zero-one scoring of incorrect and correct answers does not reflect a student's performance correctly because several erroneous rules frequently yield the right answer for some problems. By extensive error analysis performed on the original dataset (the 127 eighth graders test scores for signed-number subtraction problems) Birenbaum and Tatsuoka (1980) identified erroneous rules that were consistently applied by certain students. They rescored ones to zeros for items that students got right for the wrong reasons. The dataset used in Figures 1 through 4 are the modified dataset in which the scores of zero-one should reflect more accurately the student's performance than the original dataset of \( N = 127 \). The modified dataset was much more nearly unidimensional and had higher item-item and item-total correlations than the original, while the item-means and standard deviation remained almost the same (Birenbaum & Tatsuoka, 1982a). Fifteen erroneous rules were randomly selected from the 45 erroneous rules listed in Tatsuoka & Tatsuoka (1981) and responses based on these were added to the modified dataset. We refer to the new dataset of \( N = 142 \) as "Bugdata" hereafter.
Comparison of detection rates of ECI2z and ECI4z with respect to their 80% intervals

By using the item parameters estimated from the modified dataset, ECI2z and ECI4z for the 142 subjects in the bug dataset were calculated and plotted against the true scores. Figure 7 is the scatter plot of ECI4z against the true scores and Figure 8 is ECI2z against the same true scores. The 15 bugs are marked by a small circle "o" with the numbers and 89 real data points are marked by a plus sign "+" without being numbered.

The 80% intervals for both the ECIs and 1z are constructed and listed in Table 1 along with the means and standard deviations of the indices. These are the intervals within which, theoretically, the values of the indices associated with 80% of the non-aberrant responses should fall. The intervals are marked by broken lines in Figures 7 and 8. We may choose, as a convenient decision rule, to classify response patterns with index values outside these intervals as "aberrant." The proportions of real response patterns classified as "aberrant" (which are essentially false alarm rates) by the four indices that are shown in Table 2 along with the proportions of the 15 bugs that are detected.

The unstandardized ECI4 seemed to have the best detection rates in comparison with the other four ECIs (Tatsuoka & Linn, 1982) but lost its high rate after it was standardized. Exactly the same dataset is used in both the cases, the standardized and unstandardized fourth extended caution index. In Table 2, the false alarm rates of the four indices...
FIGURE 7: Plot of ECI4 z Against True Score for the Modified Dataset (+) and Erroneous Rules (O), and 80% Probability Interval (-1.55, 1.59).
FIGURE 8: Plot of ECI2 z Against True Score for the Modified Dataset ("+"), and Erroneous Rules ("O"), and 80% Probability Interval (-1.56, 1.59).
Table 1
The 80% Intervals of ECI$_1z$, ECI$_2z$, ECI$_4z$ and lz.

<table>
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<th>Indices</th>
<th>Mean</th>
<th>S.D.</th>
<th>80% confidence interval</th>
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<tr>
<td>ECI$_1z$</td>
<td>.001</td>
<td>1.105</td>
<td>(-1.414, 1.416)</td>
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<td>ECI$_2z$</td>
<td>.020</td>
<td>1.230</td>
<td>(-1.555, 1.594)</td>
</tr>
<tr>
<td>ECI$_4z$</td>
<td>.019</td>
<td>1.229</td>
<td>(-1.554, 1.593)</td>
</tr>
<tr>
<td>lz</td>
<td>.017</td>
<td>.619</td>
<td>(-.775, .809)</td>
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</table>
Table 2
Detection Rates of Erroneous Rules by Four Personal Indices Based on Item Response Theory with Bugdataset

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<th>Real Students</th>
<th>Erroneous Rules</th>
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<tr>
<td></td>
<td>N = 89</td>
<td>N = 15</td>
</tr>
<tr>
<td>ECI1z</td>
<td>.22</td>
<td>.60</td>
</tr>
<tr>
<td>ECI2z</td>
<td>.15</td>
<td>.53</td>
</tr>
<tr>
<td>ECI4z</td>
<td>.17</td>
<td>.67</td>
</tr>
<tr>
<td>lz</td>
<td>.18</td>
<td>.67</td>
</tr>
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</table>
vary around 20% as they should, while the correct detection rate fluctuates around 60%. Considering the fact that the false alarm rate for the 89 students by using ICI with total scores (ICI ≥ .90 and scores lower than a certain criterion, Tatsuoka & Tatsuoka, 1981) was less than 5%, the results summarized in Table 2 are not as good as we had expected. One reason for the low detection rates may be the fact that the modification procedure of rescoring in the original dataset was carried out by an intuitive error analysis, and hence there are some responses affected by persistent misconceptions left in the modified dataset. Table 3 lists the percentage of "bugs" left in the modified dataset. The total number of bugs (including repetitions) has become 42. The mean absolute value of ECI4 in the two groups described in Table 3 are 3.141 for the bugs that were not found in the modified dataset, 1.353 for the bugs left in. However, the value of ECI4, 1.353, is still substantially high in comparison with the majority of real responses in the modified dataset.

Insert Table 3 about here

Summary and Discussion

The extended caution indices, ECI1, ECI2 and ECI4 are standardized by the usual transformation,

$$ECI_m^z = \frac{ECI_m - E(ECI_m|\theta_1)}{SE(ECI_m|\theta_1)}$$

for m=1, 2, and 4.

The conditional expectation of ECI4 is a function of the \( \theta \) level, but those of the other two ECIs are identically zero. If we sample two students from different \( \theta \) levels, then it is dangerous to compare their ECI4 values in order to determine which student’s response patterns is more aberrant than the other. Moreover, the standard errors of all
Table 3

Percentage of Each Bug that was not Rescored and Remained in the November Modified Dataset (n = 8, N = 89) 356 Sets of Responses

<table>
<thead>
<tr>
<th>Bugs</th>
<th>%</th>
<th>Total Scores</th>
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<tr>
<td>1</td>
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<td>0</td>
<td>3</td>
<td>4.309</td>
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<td>0</td>
<td>2</td>
<td>4.259</td>
<td></td>
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<td>8</td>
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<td>0</td>
<td>3.059</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>3</td>
<td>4.045</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>2</td>
<td>-1.247</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>1</td>
<td>1.338</td>
<td></td>
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<table>
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<td>7</td>
</tr>
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<td>9</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>15</td>
</tr>
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*Mean of Group 1 = 3.141  S.D. = .503
Mean of Group 2 = 1.353  S.D. = .240
three ECIs are functions of $\Theta_1$ and have U shaped trend curves. This explains the past findings that the correlation of personal indices, such as the caution index, NCI, or ICI, with total scores vary according to the shapes of the total-score distributions. The findings are that if the total-score distribution has a negative skewness, then the correlation is positive, if the distribution is positively skewed, then a negative correlation results (Harnisch & Linn, 1981; Tatsuoka & Tatsuoka, 1980). Since the ECIs are natural extensions of the caution index, we can safely impute some behaviors of ECIs to these discrete personal indices as well. ECIs provide inflated values at both the extremely high and low total scores. With the standardized ECIs, the bias of the values at the extreme scores is corrected, and moreover the responses from different levels of $\Theta$ can be compared safely.

It would be ideal if the theoretical distribution of the standardized extended caution indices could be derived algebraically, but goodness-of-fit tests of the ECI$s$ with normal distributions provide satisfactory evidence that they may follow approximately normal distributions.

Regarding the detection rates of "bugs", they are unexpectedly low. We have tried to find the reason for this by investigating each response pattern in the modified dataset. The results indicate that if an otherwise normal dataset includes a considerable number of aberrant response patterns, then these patterns are no longer detectable with high probability by the ECI approach. A new method to detect such aberrant response patterns should be investigated in the future.
Rudner (1982) recently conducted a Monte Carlo study to compare the detection rates of various indices. He found that the indices based on item response theory performed consistently better with his data than the indices based on sample statistics alone. But IRT is not always applicable in practice. An advantage of ECIs in comparison with other appropriateness indices or Wright's index is that they can start from the caution index when a sample is small. Then it can be shifted to ECIs as the sample size becomes larger without loss of continuity because ECIs are natural extensions of the S-P curve theory. However, further investigation of the relationships between the original caution index and the ECIs will be needed.
References


Appendices
Captions of Appendices

Appendix I: Goodness of Fit Test for the Normal Distribution: The Stepfunction is the Cumulative Distribution of $E_{CI1}z$

Appendix II: Goodness of Fit Test for the Normal Distribution: The Stepfunction is the Cumulative Distribution of $lz$

Appendix III: Goodness of Fit Test for the Beta Distribution: The Stepfunction is the Cumulative Distribution of $E_{CIz}$

Appendix IV: Goodness of Fit Test for the Beta Distribution: The Stepfunction is the Cumulative Distribution of $E_{CI2z}$

Appendix V: Goodness of Fit Test for the Beta Distribution: The Stepfunction is the Cumulative Distribution of $E_{CI4z}$

Appendix VI: Plot of $lz$ Against True Score for the Modified Dataset ("+") and Erroneous Rules ("0"), and 80% Probability Interval (-.78, .81)

Appendix VII: Standard Error of $E_{CI1}$

Appendix VIII: Standard Error of $E_{CI2}$

Appendix IX: Standard Error of $E_{CI4}$

Appendix X: Plot of Expectation of $E_{CI4}$ Against True Score

Appendix XI: Correlation Matrix of Standardized ECIs and $lz$ with Bugdata
APPENDIX I: Goodness of Fit Test for the Normal Distribution
The Stepfunction is the Cumulative Distribution of ECII z
APPENDIX III: Goodness of Fit Test for the Normal Distribution
The Stepfunction is the Cumulative Distribution of $z$
APPENDIX III: Goodness of Fit Test for the Beta Distribution:
The Stepfunction is the Cumulative Distribution of ECI z
APPENDIX IV : Goodness-of-Fit Test for the Beta Distribution
The Stepfunction is the Cumulative Distribution of ECII z

\[ a = 4.89 \]
\[ b = 6.62 \]
\[ N = 2400 \]
APPENDIX V: Goodness of Fit Test for the Beta Distribution
The Stepfunction is the Cumulative Distribution of ECI4 z
APPENDIX VI: Plot of $J_z$ Against True Score for the Modified Dataset ("+") and Errorness Rules ("O"), and 80% Probability Interval (−.78, .81).
Appendix VII

Standard Error of ECII
Appendix VIII

Standard Error of ECI2

![Graph showing the relationship between True Score and Standard Error of ECI2.](graph.png)
Appendix IX

Standard Error of ECI4
Appendix X

Plot of Expectation of ECI4 Against True Score
Appendix XI
Correlation Matrix of Standardized ECIs and $lz$
With Bugdata

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Distribution List

Navy

1 Meryl Baker
NPRDC
Code P309
San Diego, CA 92152

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U.S. Naval Postgrad Schl
Monterey, CA 93940

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Air Force Human Resource Lab
Flying Training Division
Williams AFB, AZ 85224

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800 N. Quincy St.
Code 270
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1 Dr. William Nordbrook
Instructional Program Dev.
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Great Lakes Naval Training Cnt
Great Lakes, IL 60088

1 Ted M. I. Yellen
Technical Information Office
Code 201
Navy Personnel R&D Center
San Diego, CA 92152

1 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

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

5
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|   | Res. Devel. & Studies Branch |
|   | (OP-115) |
|   | Washington, DC 20350 |

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|   | Human Performance Sciences Department |
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|   | Orlando, FL 32813 |

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|   | San Diego, CA 92152 |

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|   | Code 54 WZ |
|   | Dpt. of Admin. Sci. |
|   | U.S. Naval Postgrad. Schl. |
|   | Monterey, CA 93940 |

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|   | Code P310 |
|   | Navy Personnel R&D Center |
|   | San Diego, CA 92152 |

| 1 | Dr. Robert Wisher |
|   | Code 309 |
|   | Navy Personnel R&D Center |
|   | San Diego, CA 92152 |

| 1 | Dr. Martin F. Wiskoff |
|   | Navy Personnel R&D Center |
|   | San Diego, CA 92152 |

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|   | 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 |

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

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

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|   | 5001 Eisenhower Ave. |
|   | Alexandria, VA 22333 |

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

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|   | 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

1 Dr. Robert Sasmor  
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  
HQ, AFHRL (AFSC)  
Brooks AFB, TX 78235

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

1 Res. & Measurement Div.  
Res. Branch, AFMPC/MPCYPR  
Randolph AFB, TX 78148

1 Dr. Malcolm Ree  
AFHRL/MP  
Brooks AFB, TX 78235

1 Dr. Marty Rockway  
Technical Director  
AFHRL(OT)  
Williams AFB, AZ 58224

Marines

1 H. William Greenup  
Education Advisor (E031)  
Education Center, MCDEC  
Quantico, VA 22134

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

1 Director, Off. of Manpwr Util.  
HQ, Marine Corps (MPU)  
BCB, Bldg. 2009  
Quantico, VA 22134

1 HQ, Marine Corps  
Code PML-20  
Washington, DC 20380

1 Special Ast. for Marine Corps  
Code 100M  
Office of Naval Research  
800 N. Quincy St.  
Arlington, VA 22217

1 Maj. Michael Patrow, USMC  
HQ, Marine Corps  
(Code MPI-20)  
Washington DC 20380

1 Dr. A.L. Slafkosky  
Scientific Advisor (Code RD-1)  
HQ, Marine Corps  
Washington, DC 20380

Coast Guard

1 Chief, Psych. Res. Branch  
Coast Guard (G-P-1/2/TP42)  
Washington, DC 20593

1 Thomas A. Warm  
Coast Guard Inst.  
P.O. Substation 18  
Oklahoma City, OK 73169
<table>
<thead>
<tr>
<th>Name</th>
<th>Address</th>
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<tbody>
<tr>
<td>Dr. Susan Chipman</td>
<td>Learning &amp; Development NIE 1200 19th St. NW Washington, DC 20208</td>
</tr>
<tr>
<td>John Mays</td>
<td>National Inst. of Ed. 1200 19th St. NW Washington, DC 20208</td>
</tr>
<tr>
<td>Richard McKillip</td>
<td>Personnel R&amp;D Center Personnel Management 1900 E. St. NW Washington, DC 20415</td>
</tr>
<tr>
<td>William J. McLaurin</td>
<td>66610 Howie Court Camp Springs, MD 20031</td>
</tr>
<tr>
<td>Dr. Arthur Melmed</td>
<td>National Inst. of Ed. 1200 19th St. NW Washington, DC 20208</td>
</tr>
<tr>
<td>Dr. Andrew R. Molnar</td>
<td>Sci. Ed. Dev. &amp; Res. NSF Washington, DC 20550</td>
</tr>
<tr>
<td>Dr. Joseph Psotka</td>
<td>NIE 1200 19th St. NW Washington, DC 20208</td>
</tr>
<tr>
<td>Wallace Sinaiko</td>
<td>Program Director MRHS Smithsonian Institution 801 N. Pitt Street Alexandria, VA 22314</td>
</tr>
<tr>
<td>Dr. Vern W. Urry</td>
<td>Personnel R&amp;D Center Office of Personn. Mngmnt. 1900 E St. NW Washington, DC 20415</td>
</tr>
<tr>
<td>Frank Withrow</td>
<td>US office of Ed. 400 Maryland Ave. SW Washington, DC 20202</td>
</tr>
<tr>
<td>Dr. Joseph L. Young</td>
<td>Dir. Memory &amp; Cognitive Processes NSF Washington, DC 20550</td>
</tr>
<tr>
<td>Other Department of Defense</td>
<td></td>
</tr>
<tr>
<td>Defense Technical Information Center</td>
<td>Cameron Station, Bldg 5 Alexandria, VA 22314 Attn:TC</td>
</tr>
<tr>
<td>Dr. William Graham</td>
<td>Testing Directorate MEPCOM/MEPCT-P Ft. Sheridan, IL 60037</td>
</tr>
<tr>
<td>Dr. Wayne Sellman</td>
<td>Office of the Asnt. Sec. of Defense (MRA &amp; L) Room 2B269, The Pentagon Washington, DC 20301</td>
</tr>
<tr>
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<td>1400 Wilson Blvd. Arlington, VA 22209</td>
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<td>Dr. James Algina</td>
<td>University of Florida Gainsville, FL 32611</td>
</tr>
<tr>
<td>Dr. Erling B. Andersen</td>
<td>Dept. of Statistics Studiestraede 6 1455 Copenhagen DENMARK</td>
</tr>
</tbody>
</table>
1 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

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

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

1 1Psych. Res. Unit
Dept. of Defense (Army)
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

1 Mr. Avron Barr
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Issac Bejar
Educational Testing Serv.
Princeton, NJ 08450

1 Dr. Menucha Birenbaum
School of Ed.
Tel Aviv University
Ramat Aviv - Box 39040
Tel Aviv 69978
ISRAEL

1 Dr. Werner Birke
DezWP im Streitkraefteamt
Postfach 20 50 03
D-5300 Bonn 2
WEST GERMANY

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 FP0
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
University of California
Los Angeles, CA 90024

1 Dr. John B. Carroll
Psychometric Lab
Univ. of N. Carolina
Davie Hall 013A
Chapel Hill, NC 27514
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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, WI 53201
Dr. David Miller  
Graduate School of Ed.  
UCLA  
Los Angeles, CA  90024

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

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

Dr. Anthony J. Nitko  
School of Ed.  
Division of Ed. Studies  
University of Pittsburgh  
5003 Forbes Quadrangle  
Pittsburgh, PA  15260

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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. Rosenbaum  
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  92039

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  
HUMARRO  
300 N. Washington St.  
Alexandria, VA  22314

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

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

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

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

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

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

1 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. Illinois University
Carbondale, IL  62901