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ABSTRACT

Some stochastic approximation procedures are considered in relation to the problem of choosing a sequence of test questions to accurately estimate a given examinee's standing on a psychological dimension. Illustrations are given evaluating certain procedures in a specific context. (Author/CK)

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TAILORED TESTING, AN APPLICATION OF STOCHASTIC APPROXIMATION

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TAILORED TESTING, AN APPLICATION OF STOCHASTIC APPROXIMATION*

This paper deals with a rather difficult problem in educational (or mental) testing. However, the statistical reader need not be familiar with the basic ideas of classical mental test theory--in particular, the notions of "true score" and "reliability." The inconsequence of the classical theory here is surprising. Perhaps this indicates that the approach to be used is no less fundamental than the classical theory itself.

Consider the educator or psychologist whose purpose is to measure "ability" or achievement (or other trait) for a number of individuals. Let us denote the trait being measured by θ and choose a scale of measurement so that θ varies from $-\infty$ to $+\infty$. For present purposes, θ is not a chance variable; it is simply a parameter describing a person.

The educator has a large bag full of test questions called "items." Let us only consider items that are scored "right" or "wrong." Denote the score on item i by $u_i = 1$ or 0. Think of testing just one person; or if a group is to be tested, consider each person individually. We plan to use the individual's responses to a selected subset of the items in order to estimate his value of θ.

If we are to do this, we need to know something about how his responses depend on his ability, that is, something about the function

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$$P_i \equiv P_i(\theta) \equiv \text{Prob}(u_i=1|\theta) \quad . \tag{1}$$

This function is called the trace line or item characteristic function or item characteristic curve [5, chapts. 16-17; 4]. It seems reasonable to assume that the function is continuous and monotonic increasing--the higher the ability level, the more the probability of success.

Typically, the item characteristic function is assumed to be a logistic function, or a cumulative normal distribution function; or possibly one of these functions so modified as to have its lower asymptote greater than 0. Some typical item characteristic curves are shown in Figure 1. The meaning of the descriptive parameters a, b, and c need not concern us at this point.

Although the unmodified curves are cumulative distribution functions, it is usually not helpful to think of them in this way. The item characteristic function is best thought of as the regression of the item score u_i on θ.

It is common to assume that for any set of items the conditional probability of success on all the items when θ is fixed is simply the product of the separate probabilities of success. This assumption is known as the assumption of local independence. It implies that items are uncorrelated when ability is held constant (not that they are uncorrelated in ordinary groups of examinees).

To see the reason for the assumption, let us suppose on the contrary that P_{ij}, the probability of simultaneous success on items i and j,

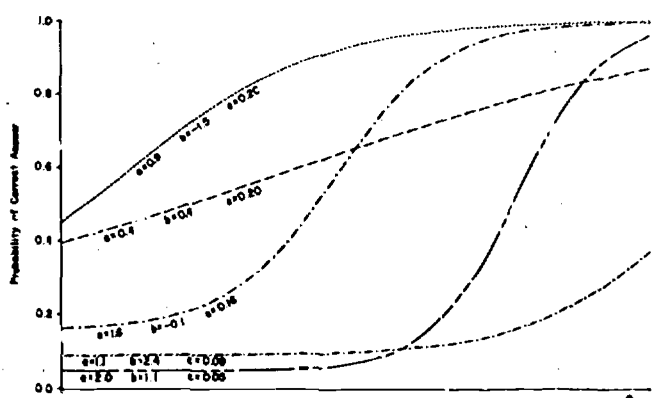

Figure 1. Probability of correct answer as a function of ability, as estimated for five SAT Verbal Items.

is greater than P_iP_j . This would mean that even when θ is fixed, there is some psychological dimension that helps to determine whether items i and j are answered correctly. In other words, for fixed θ , items i and j constitute a two-item test measuring some psychological dimension other than θ . This is just the sort of situation that the assumption of local independence is intended to rule out. For simplicity, we wish to consider tests that measure a single psychological dimension rather than tests that measure several at the same time.

Let us suppose that the items in the educator's bag have been extensively pretested, so that the shape of the item characteristic curve for each item is known to a good approximation. Let us select from the bag a large set of items whose characteristic curves differ only by a translation along the θ -axis. Thus, we may describe item i by a parameter b_i , called the <u>difficulty</u> of item i , defined by the equation

$$P_i(b_i) = \alpha \quad ,$$

where α is some constant, possibly 1/2, chosen by the statistician. Since all characteristic curves differ only by a translation, the curve for item i will be written as $P(\theta - b_i)$.

Suppose now that we administer many items to a particular student. By trial and error, we can find approximately the item difficulty level b at which the student has probability of success α . Once we have done this, we can now estimate the student's ability level as approximately $\theta = b$.

As I have outlined it, the problem of estimating θ is a standard problem in stochastic approximation [8]. Specifically, the stochastic approximation problem is to choose a sequence of items--that is, a sequence of b_i --in such a way that we can estimate θ from the resulting sequence of u_i .

The item sequence constitutes a tailored test, so called because the items are chosen specifically in an attempt to measure one particular individual as effectively as possible.

Although tailored testing can be carried out in a paper-and-pencil situation, it is relatively difficult to do so. On the other hand, if a computer is available, as it is in many educational institutions, then a large number of test items can be stored in the computer. Once an effective rule for selecting items is provided, the computer can easily produce a test specially tailored to the ability level of each individual being tested.

According to the Robbins-Monro stochastic approximation procedure, the difficulty of the $(v + 1)$ -st item is to be determined by the rule

$$b_{v+1} = b_v + d_v(u_v - \alpha) \qquad (2)$$

where $d_1, d_2, \ldots$ is a suitable decreasing sequence of positive constants chosen in advance by the statistician [8, 7, 3]. Typically,

$$d_v = d_1/v \quad , \qquad (3)$$

a harmonic sequence. Each d_v determines a "step size" by which item difficulty is adjusted--upwards if $u_v = 1$, downwards if $u_v = 0$.

This rule for choosing items has the following effect: Each time the student answers an item correctly, the next item administered is chosen to be more difficult. Each time his answer is incorrect, the next item is chosen to be easier. The increment or decrement in item difficulty is large at the start of the testing, when little is known about the student's ability level, and becomes smaller as testing proceeds. All these properties of the rule seem intuitively desirable.

Unfortunately, a strict adherence to this rule would require storing 2^n items in the computer before beginning to test, where n is the total number of items (presumed to be fixed in advance) to be administered to a single examinee. In most tests composed of dichotomously scored items, $n \geq 25$.

In order to avoid preparing and storing 2^n items, a method called the up-and-down method, originally designed for testing explosives, can be used [8]. In this method, the rule for choosing items is the same as under the Robbins-Monro procedure except that d_v in (2) is replaced by some predetermined fixed step size d .

When $\alpha = 0.5$, the up-and-down rule becomes

$$b_{v+1} = \begin{cases} b_v + d & \text{if } u_v = 1 \text{ ,} \\ & \text{with probability } P(\theta - b_v) \text{ ,} \\ b_v - d & \text{if } u_v = 0 \text{ ,} \\ & \text{with probability } Q(\theta - b_v) \text{ ,} \end{cases} \tag{4}$$

where $Q = 1 - P$. Figure 2 may be helpful in visualizing the sequence of items administered. It is assumed that the difficulty of the first item

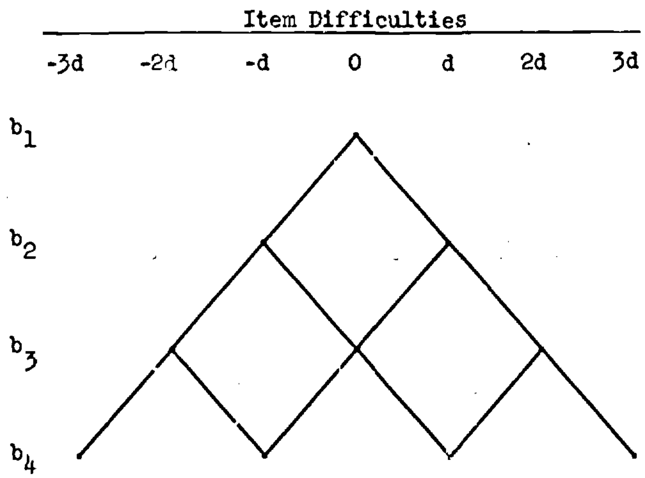

Figure 2. Possible sequences of item difficulties. When the difficulty of the first item is $b_1 = 0$, any path proceeding downwards from the apex represents a possible sequence.

is $b_1 = 0$. Any downward path starting at the apex of the figure represents a possible sequence of item difficulties for a single individual.

In principle, at least, we must store one item in the computer for each intersection shown in Figure 2. Thus if n items are to be administered to the examinee, the total number of items to be prepared and stored before testing should be $n(n + 1)/2$. It is quite practical to carry on computer-based testing with the up-and-down method, especially if a few shortcuts are taken to reduce the total number of items required.

It is clear from Figure 2 that the up-and-down method corresponds to a random walk. The transition probabilities $P(\theta - b_v)$ and $Q(\theta - b_v)$ are stationary. They depend on b_v , but they do not depend on v when b_v is given.

The up-and-down method has been widely recommended and used in bio-assay applications. Dixon and Mood [2] obtained a large-sample approximation to the maximum likelihood estimator of θ for the up-and-down method, on the assumption that $P(\theta)$ is a normal ogive. The likelihood function is

$$L(u_1, u_2, \ldots, u_n | \theta; b_1, b_2, \ldots, b_n) = \prod_{v=1}^{n} [P(\theta - b_v)]^{u_v} [Q(\theta - b_v)]^{1-u_v} , \quad (5)$$

where the value of b_v for $v > 1$ depends on the values of u_{v-1} , $u_{v-2}, \ldots, u_1$, as shown by equation (4).

Consider the following three simple methods for scoring the student's responses to the items administered:

1. The "final-difficulty score," b_{n+1}, the difficulty of the (n + 1) -th item administered, as defined by equation (2). Robbins and Monro showed that for suitable sequences $\{d_v\}$, the score b_v converges in probability to θ as v becomes large.

2. The "number-right score," $\sum_{v=1}^{n} u_v$, or the "proportion-right score," $\frac{1}{n} \sum_{v=1}^{n} u_v$. The former is the score most commonly used in scoring conventional mental tests.

3. The "average-difficulty score," $X = \frac{1}{n} \sum_{v=2}^{n+1} b_v$. This score is simply the average of the difficulty parameters of the items administered to the student, omitting the first (since the first item is the same for all examinees) and including b_{n+1}.

[Before going ahead, the reader may wish to make a guess as to the relative merits of these three scoring methods for the up-and-down (fixed step size) procedure.]

When the step size shrinks appropriately as n increases, as in the Robbins-Monro procedure, b_{n+1} is a good estimator for θ. When the step size is fixed, as in the up-and-down method, b_{n+1} is no longer a consistent estimator for θ, nor does its sampling variance approach zero as n becomes large.

Surprisingly, it turns out that when step size is fixed number-right score is perfectly correlated with b_{n+1}.

Brownlee, Hodges, and Rosenblatt [1] have shown that the average-difficulty score is asymptotically equivalent to the maximum likelihood estimator for θ found by Dixon and Mood. Although no optimum small-sample properties have been proven for the average-difficulty score, it appears to be the score of choice for the up-and-down method at present. (See Wetherill [9] for empirical studies of Robbins-Monro, up-and-down, and other procedures.)

The remaining problem for discussion here is the evaluation of different testing procedures and of the different choices of parameters such as d and α.

It frequently happens that organizations test similar groups of students year after year. In this case, they have available an excellent prior distribution for the parameter θ based on records of past performance. In such situations, the careful design of a tailored testing procedure would certainly be based on a Bayesian approach (see Owen [6]).

The Bayesian approach will not be used here. For one thing, it complicates the mathematics. For present purposes, it seems better to present results in a form that can be used by a variety of different readers having a variety of prior distributions for θ.

Brownlee, Hodges, and Rosenblatt have a recursive method for evaluating $\mathcal{E}(X|\theta)$, the expected score for any given θ; also for evaluating $\sigma^2(X|\theta)$, its conditional variance. For example,

$$\begin{aligned}\mathcal{E}[X_{v+1}-(v+1)\theta \mid \theta;\ b_1=b] = {} & P(\theta-b)\ \mathcal{E}[X_v-v\theta \mid \theta;\ b_1=b+d] \\ & + Q(\theta-b)\ \mathcal{E}[X_v-v\theta \mid \theta;\ b_1=b-d] \\ & + (d-\theta+b)\ P(\theta-b) - (d+\theta-b)\ Q(\theta-b) \quad .\end{aligned} \tag{6}$$

It is quite practical, even for sizeable n , to compute recursively on a computer the desired expectations and sample variances, for each of a variety of values of θ .

This brings us to an interesting problem in statistical inference. In bioassay θ is typically the dose of a drug at which $P(\theta) = \alpha$. Usually, any bias in the estimation procedure is a serious problem. In bioassay, it would seem appropriate to use the mean-square error

$$MSE = \mathcal{E}(X - \theta)^2 \qquad (7)$$

$$= \sigma^2(X|\theta) + [\mathcal{E}(X|\theta) - \theta]^2$$

as an appropriate measure of the effectiveness of a particular procedure.

In mental testing, on the other hand, biased estimates of θ are perfectly satisfactory provided the bias is the same for each student tested. The fact is that in most situations the origin and the unit of measurement for measuring ability is arbitrary. Thus the parameter

$$\theta^* = A + B\theta \quad ,$$

where A and B are any constants with $B > 0$, is usually quite as satisfactory as the parameter θ itself. For example, the number-right score $\sum^n u_v$ is just as satisfactory an estimator as the proportion-right score $\frac{1}{n}\sum^n$ [illegible] ..hough these scores clearly do not estimate the same parameter. Both scores are satisfactory despite the fact that the sampling variance of the first is n^2 times as large as the sampling variance of the second.

If we cannot discriminate among estimation procedures on the basis of bias and sampling variance, how are we to evaluate different estimation procedures with respect to each other? If the purpose of the test is to separate students with higher θ from those with lower θ, it is clear that in some sense we would like

$$\frac{\mathcal{E}(X|\theta_2) - \mathcal{E}(X|\theta_1)}{\sigma(X|\theta_1)}$$

to be large, where $\theta_2 = \theta_1 + \Delta_\theta$ and Δ_θ is a small increment in θ, sufficiently small so that $\sigma(X|\theta_2)$ is approximately equal to $\theta(X|\theta_1)$. For present purposes, the effectiveness of a psychological testing procedure will be described by $I_x(\theta)$, a function of θ, where

$$I_x(\theta) = \frac{K[\mathcal{E}(X|\theta+\Delta_\theta) - \mathcal{E}(X|\theta)]^2}{\sigma^2(X|\theta)} \quad . \qquad (8)$$

The constant of proportionality K and the choice of Δ_θ affect the size of $I_x(\theta)$ but are irrelevant for comparing different testing procedures as long as the same values are used for each procedure.

The sorts of results obtained are illustrated in Figures 3 and 4. The ability level of the examinee is shown along the horizontal axis in each figure. The effectiveness of each test procedure is shown along the vertical axis (although different numerical scales are used in the two figures). Each curve shows the effectiveness of a procedure as a function of ability level.

The curves labeled "standard" are displayed to provide familiar bench marks. Each standard test is a conventional (not a tailored) test, composed

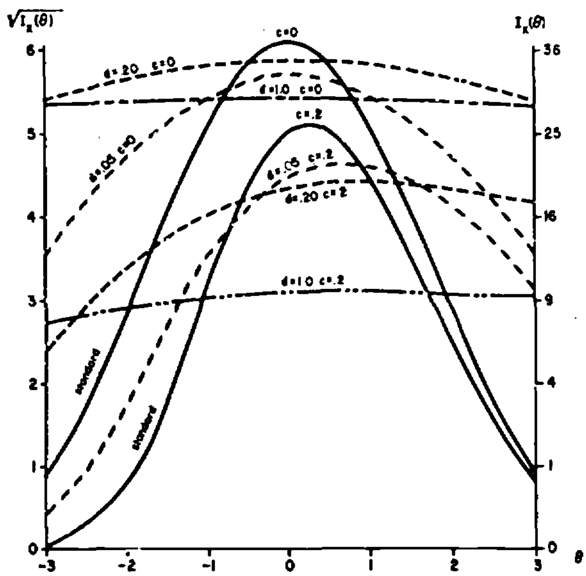

Figure 3. A comparison of measurement efficiency for the up-and-down method when there is chance success (c = .2) and when there is not (c = 0). n = 60 .

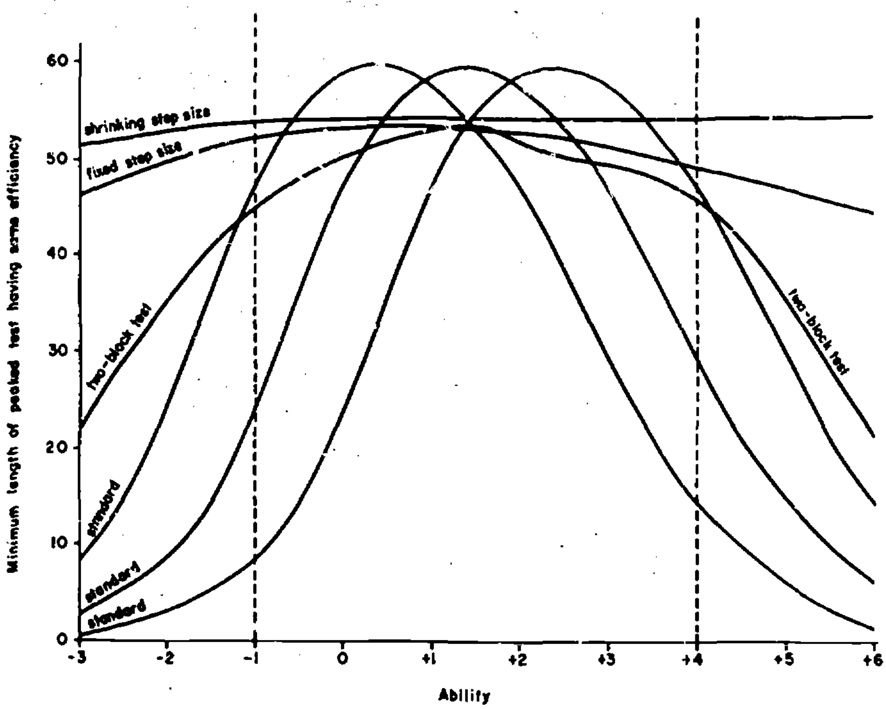

Figure 4. Efficiency of three 60-item tailored testing procedures as compared to that of three conventional 60-item peaked ("standard") tests, as a function of examinee ability.

entirely of items of equal difficulty, the score being the number of right answers. For such a test, the number of right answers is known to be a sufficient statistic for estimating θ . Thus a horizontal line passing through the maximum of a standard curve represents an upper limit to the effectiveness of any test procedure based on dichotomously scored items--an upper limit that ordinarily would be attainable only if the examinee's true value of θ were known in advance of the testing.

The tests shown in Figures 3 and 4 all require administering $n = 60$ items to each student. The three broken curves at the top of Figure 3 display the effectiveness of three tailored tests with fixed step sizes $d = .05$, .20, and 1.0. In the situation illustrated, a step size of .05 is seen to be too small. It seems that a step size around $d = .20$ is most effective for the circumstances considered. A step size of 1.0 would be necessary, however, if it were desired to measure accurately at ability levels above $\theta = 4$ or below $\theta = -4$.

The three curves labeled $c = 0$ describe a tailored testing with items that cannot be answered correctly by guessing. The curves labeled $c = .2$ describe tailored tests composed of items that will be answered correctly at least 20 percent of the time, even by examinees at very low ability levels. The figure shows that when low-ability students can sometimes answer items correctly (whether by random or nonrandom guessing), there is a considerable loss of measurement effectiveness. A part of this loss may be recovered by a more suitable choice of the parameter α ; however, most of the loss is irretrievable.

Figure 4 is similar to Figure 3. The vertical axis still measures the effectiveness of the procedure, although expressed in different units. All the curves relate to tests composed of items that may be successfully answered by random guessing. The curve labeled "shrinking step size" represents the "best" Robbins-Monro procedure found for a certain purpose after investigating a large number of such procedures. The "fixed step size" curve represents similarly the "best" of a large number of up-and-down procedures. The "two-block test" represents a "best" two-stage procedure. The first stage is the administration of a single conventional test with all items at the same difficulty level. The number-right score on this "routing test" is used to assign the examinee to take a single second-stage test, which again is a conventional test consisting of items all at the same difficulty level.

The results displayed in the figure show, among other things, that the up-and-down procedure with fixed step size is in this case almost as efficient as the Robbins-Monro procedure. (Note that figures are displayed here to illustrate types of conclusions obtainable, not to establish conclusions for themselves.)

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13. ABSTRACT

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