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THE STANDARD ERROR OF EQUIPERCENTILE EQUATING

Frederic M. Lord

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Personnel and Training Research Programs
Psychological Sciences Division
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The Standard Error of Equipercentile Equating

Abstract

The standard error of an equipercentile equating is derived for four different situations. Some numerical results are checked by Monte Carlo methods. Numerical standard errors are computed for two sets of real data.

The Standard Error of Equipercentile Equating*

It is frequently desired to use scores on two or more forms of the same test interchangeably. If the test forms differ in difficulty or in other ways, some transformation of the raw test scores must be made to adjust for these differences. Transformations that (attempt to) make scores on different forms interchangeable are called equatings. In equipercentile equating, these transformations are determined by the requirement that for some specified population, the cumulative frequency distribution of the transformed scores shall (theoretically) be the same regardless of the test form administered.

In practice, some empirical procedure is used to implement this theoretical definition for an actual sample of examinees. Sampling fluctuation in the resulting empirical equating is the subject of concern here.

Consider the following empirical large-sample equipercentile equating procedure:

1. Administer tests X and Y to N examinees. Score both tests.

2. Given any fixed x_o, find the score y' that has the same sample cumulative frequency.

3. Assert that the scores (x_o, y') are asymptotically equated. (This procedure is slightly biased since Nq observations lie below x_o and only $Nq - 1$ observations lie below y'. We ignore this, since it will not affect the asymptotic variance.)

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We must now find the asymptotic sampling variance of this y' for fixed x_o. We will consider first a (unrealistic) case where the test score is a continuous variable, then a more usual case where the test score is nonnegative integer.

If tests X and Y are given to the same examinees, there is likely to be a practice effect or a fatigue effect on the second test administered. To avoid this, it is common to give tests X and Y to different random samples from the same population of examinees. We consider this case first.

1. Continuous Case, Two Groups

Let $F(x)$ and $G(y)$ denote the cumulative frequency distribution of score x and score y in the population. We administer test X to a sample of N_1 examinees and find that in the sample a proportion q of these fall below the chosen fixed value x_o. Having administered test Y to a sample of N_2 examinees from the same population, we denote the q -th order statistic in this sample by y' and assert that y' is equivalent (equated) to x_o. We wish to find the asymptotic sampling variance of y' (it is always to be understood that x_o is fixed).

For fixed q, y' is asymptotically normally distributed with mean $\mu_{y'|q}$ determined by the relation

$$G(\mu_{y'|q}) = q \tag{1}$$

and variance

$$\sigma^2_{y'|q} = pq/N_2(g(\mu_{y'|q}))^2 \quad , \tag{2}$$

where $p \equiv 1 - q$ and $g(y)$ is the probability density at y (Kendall & Stuart, 1969, Sections 14.11-14.12). When q is random, a well-known identity gives

$$\text{Var } y' \equiv \text{Var}(\mu_{y'|q}) + \mathcal{E}(\sigma^2_{y'|q}) \quad . \tag{3}$$

From (1)

$$\frac{d}{dq}\mu_{y'|q} = \frac{1}{g(\mu_{y'|q})} \quad .$$

By the delta method, we find

$$\text{Var}(\mu_{y'|q}) = PQ/N_1 g_o^2 \tag{4}$$

where Q is defined by

$$Q \equiv F(x_o) \quad , \tag{5}$$

$P \equiv 1 - Q$, $g_o \equiv g(y_o)$, and y_o is defined by

$$G(y_o) \equiv Q \quad . \tag{6}$$

To evaluate $\mathcal{E}\sigma^2_{y'|q}$ we rewrite (2), expand in series, and neglect higher order terms:

$$\mathcal{E}\sigma^2_{y'|q} = \mathcal{E}\,\frac{pq}{N_2 g_o^2 \left(1 - \dfrac{g - g_o}{g_o}\right)^2}$$

$$\equiv \mathcal{E}\,\frac{pq}{N_2 g_o^2}\left(1 - 2\,\frac{g - g_o}{g_o} + \ldots\right)$$

$$\doteq \mathcal{E}\,\frac{p - p^2}{N_2 g_o^2} = \frac{1}{N_2 g_o^2}\left(P - \mathrm{Var}\;p - P^2\right) \doteq \frac{PQ}{N_2 g_o^2} \qquad (7)$$

where $g \equiv g(\mu_{y'|q})$. Substituting (4) and (7) into (3) we have finally

$$\mathrm{Var}\;y' \doteq \frac{PQ}{g_o^2}\left(\frac{1}{N_1} + \frac{1}{N_2}\right) \quad . \qquad (8)$$

2. Discrete Case, Two Groups

Consider next the case where scores x and y are nonnegative integers. For convenience, we will always pick x_o to be an integer plus 0.5. Let $F(x)$ and $G(y)$ be distribution functions continuous to the right of each integer and let y_o be the integer defined by the relation $G(y_o - 1) < Q \equiv F(x_o) \leq G(y_o)$. It will ordinarily be asymptotically infinitely unlikely that $G(y_o) = Q$; for simplicity, we will assume hereafter that $G(y_o) > Q$.

If we now define y' as in the preceding section, we are sure that integers y' and y_o will be equal for sufficiently large N . This means to the usual order of approximation that y' will have an asymptotic variance of zero. Let us use linear interpolation to define a value y'' as follows:

$$y'' = y' - 0.5 + \frac{q - \hat{G}^-}{\hat{g}} \tag{9}$$

where $\hat{G}^-$ is the observed proportion of Y scores <u>below</u> the integer y' and $\hat{g}$ is the observed proportion of scores at y' . We will in the discrete case assert that y'' is equated to x_o . It is the asymptotic variance of y'' that is now required.

As noted above, the variance of y' is asymptotically zero. The proportions q , $\hat{g}$, and $\hat{G}^-$ are asymptotically normally distributed with known variances and covariances:

$$\sigma_q^2 = PQ/N_1 \quad , \quad \sigma_{\hat{g}}^2 = g_o(1 - g_o)/N_2 \quad , \quad \sigma_{\hat{G}^-}^2 = G^-(1 - G^-)/N_2 \quad ,$$

$$\sigma_{q\hat{g}} = 0 \quad , \quad \sigma_{q\hat{G}^-} = 0 \quad , \quad \sigma_{\hat{g}\hat{G}^-} = - g_o G^-/N_2 \quad .$$

Now

$$dy'' = \frac{dq}{\hat{g}} - \frac{d\hat{G}^-}{\hat{g}} - \frac{q - \hat{G}^-}{\hat{g}^2} d\hat{g} \quad .$$

By the delta method, we obtain finally

$$\text{Var } y'' \doteq \frac{1}{g_o^2}\left[\text{Var } q + \text{Var } \hat{G}^- + \left(\frac{Q - G^-}{g_o}\right)^2 \text{Var } \hat{g} + 2\,\frac{Q - G^-}{g_o}\,\text{Cov}\,(\hat{g}, \hat{G}^-)\right]$$

$$= \frac{PQ}{N_1 g_o^2} + \frac{1}{N_2 g_o^2}\left[G^- - Q^2 + \frac{(Q - G^-)^2}{g_o}\right]$$

$$= \frac{1}{g_o^2}\left[\frac{PQ}{N_1} + \frac{PQ}{N_2} - \frac{1}{N_2} \cdot \frac{(G_o - Q)(Q - G^-)}{(G_o - G^-)}\right] \qquad (10)$$

where $G^- \equiv G_o - g_o$. Note that the last fraction in (10) approaches zero as $g_o \to 0$. Thus as g_o becomes small, (10) approaches (8), the variance for the continuous case.

3. Discrete Case, One Group

If there were no practice or fatigue effect, it would be more efficient to administer both tests to the same students. In order to see how much difference this would make, we derive the sampling variance of (9) for this case.

Let a , b , c , d , k , m be sample frequencies as defined by the accompanying diagram and let α , β , γ , δ , κ , and μ be the corresponding population

	$x < x_o$	$x > x_o$
$y > y_o$	b	a
$y = y_o$	k	m
$y < y_o$	d	c

proportions. In the present notation $q \equiv b + k + d$, $\hat{G}^{-} \equiv c + d$, and $\hat{g} \equiv k + m$, so (9) becomes

$$y'' = y' - 0.5 + \frac{b + k - c}{k + m} \quad . \tag{11}$$

The sample frequencies are again asymptotically multivariate normal with the familiar variances and covariances: $\sigma_b^2 = \beta(1 - \beta)/N$ $\sigma_{bc} = -\beta\gamma/N$, and so forth.

As before,

$$dy'' = \frac{db + dc}{k + m} + \frac{m - b + c}{(k + m)^2} dk - \frac{k + b - c}{(k + m)^2} dm \quad .$$

Using the delta method, we finally obtain after some algebra

$$\mathrm{Var}\ y'' = \frac{1}{Ng_o^3} [\mu\kappa + (\beta + \gamma)g_o + (\beta - \gamma)^2] \tag{12}$$

where $g_o \equiv \mu + \kappa$.

If x and y are independently distributed, (12) becomes the same as (10) with $N_1 = N_2 = N$.

4. Continuous Case, One Group

When x and y are continuous, we deal with sample frequencies a, b, c, d, as defined in the accompanying diagram.

	$x < x_o$	$x > x_o$
$y > y'$	b	a
$y < y'$	d	c

The corresponding population proportions are denoted by α, β, γ, δ; for example $\delta = \Phi(x_o, y')$ where $\Phi(x,y)$ is the cumulative distribution function of x and y.

Since y' is to be the q-th order statistic, as in section 1, where $q \equiv b + d$, it follows that given x_o, y' must always be chosen so that $b = c$. For given x_o, then, the frequency distribution of y' is proportional to the probability of finding one person at y', c persons with $x < x_o$ and $y > y'$, and c persons with $x > x_o$ and $y < y'$. Writing $M \equiv N - 1$, this probability is proportional to $g(y')$ times the sum, over all possible values of c, of the multinormal probability

$$\frac{M!\ \beta^c \beta^c (\alpha + \delta)^{M-2c}}{c!\ c!\ (M - 2c)!} \quad . \tag{13}$$

Using Stirling's approximation to the factorials, the distribution of y' for M even is

$$g(y') \sum_{c=o}^{M/2} \frac{M^{M+\frac{1}{2}} \beta^{c} \gamma^{c} (1 - \beta - \gamma)^{M-2c}}{2\pi c^{2c+1} (M - 2c)^{M-2c+\frac{1}{2}}} \tag{14}$$

Taking logs under the summation sign, we have that the asymptotic distribution of y' is proportional to

$$\sum_{c=o}^{M/2} \exp(\log A)$$

where

$$\log A \equiv \log g(y') - \frac{1}{2}\log(1 - 2C) - \log 2\pi - \log M - \log C$$
$$+ M[C \log \beta\gamma + (1 - 2C) \log(1 - \beta - \gamma) - 2C \log C$$
$$- (1 - 2C) \log(1 - 2C)]$$

where $C \equiv c/N$.

Expand A in powers of $\tilde{y} \equiv y' - y_o$ and $\tilde{c} \equiv C - \gamma_o$. Using a zero subscript to denote quantities evaluated at y_o (note that $\beta_o \equiv \gamma_o$, but that $d\beta/dy_o \neq d\gamma/dy_o$) and dropping terms of lower order than M , we find

$$\log A \cong - \frac{M}{2\gamma_o(1 - 2\gamma_o)} [\frac{1}{2} \{(2\gamma_o' - g_o)^2 + g_o^2(1 - 2\gamma_o) \tilde{y}^2$$
$$- 2(2\gamma_o' - g_o) \tilde{y}\tilde{c} + 2\tilde{c}^2] \tag{15}$$

where $\gamma_o' \equiv d\gamma_o/dy_o$.

As in Feller (1950, Section VII.2), we see from (15) that c and y' are asymptotically bivariate normal. Writing $\lambda \equiv 1 - 2\gamma_o$, and $h \equiv 2\gamma_o' - g_o$, we see from (15) that

$$M\sigma^2_{y'}(1 - \rho^2) \doteq \frac{2\gamma_o\lambda}{h^2 + g_o^2\lambda} \quad , \tag{16}$$

$$M\sigma^2_c(1 - \rho^2) \doteq \frac{\gamma_o\lambda}{2} \quad , \tag{17}$$

$$\frac{M\rho}{(1 - \rho^2)\sigma_{y'}\sigma_c} \doteq \frac{h}{\gamma_o\lambda} \quad , \tag{18}$$

where ρ is the correlation between y' and c . Squaring the last equation and multiplying by the other two, we find that

$$\rho^2 \doteq \frac{h^2}{h^2 + g_o^2\lambda} \quad , \quad 1 - \rho^2 \doteq \frac{g_o^2\lambda}{h^2 + g_o^2\lambda} \quad . \tag{19}$$

Thus finally, from (16) and (19),

$$\sigma^2_{y'} \doteq \frac{2\gamma_o}{Ng_o^2} \quad . \tag{20}$$

Note that as the correlation between x and y approaches 1.0, the proportion γ_o approaches zero and $\sigma^2_{y'}$ in (20) vanishes. We may also see that in (12) when $\kappa + \mu \equiv g_o$ becomes small so that $\beta \to \gamma$, Var y'' for the discrete case with one group approaches (20).

When the correlation between x and y is zero, (20) is the same as (8) with $N_1 = N_2$.

5. Numerical Results

Formulas (8) and (20) for the continuous case are simpler than formulas (10) and (12) for the discrete case. We will give first some numerical results from formulas (8) and (20).

A Monte Carlo study was carried out by drawing $N = 1000$ pairs of pseudo-random standardized normal bivariate deviates (x,y) from a population with a correlation of $\rho_{xy} = .90$ (this is a typical correlation between parallel test forms). From this sample of 1000 cases the equated value of y' was found separately for $x_o = 0, 0.5, 1.0, 1.5, 2.0, 2.5$. The foregoing was repeated 1000 times with independently drawn bivariate samples. For each given x_o, the empirical standard deviation $s_{y'}$ was computed.

The resulting standard errors (not variances) are presented in the fourth column of Table 1. The corresponding theoretical values from (20) are shown in the third column. There is excellent agreement between theoretical and Monte Carlo results.

The second column of Table 1 shows the standard error, according to (8), when tests X and Y are administered to different examinees rather than to the same examinees. We see that this does not entail as serious a loss of equating accuracy as might have been feared. In view of the likelihood of practice and fatigue effects, it seems that the methods of Sections 1 and 2 should be used whenever possible, rather than the methods of Sections 3 and 4.

Table 1

Standard Errors of Equipercentile Equating for Normally Distributed Variables

	Standard Error		
	Eq. (8) [or (20), $\rho_{xy}=0$]	$\rho_{xy} = .90$	
x_o	$N_1 = N_2 = 1000$	Eq. (20)	Monte Carlo
0	.056	.030	.029
.5	.059	.032	.032
1.0	.068	.038	.037
1.5	.086	.052	.053
2.0	.124	.080	.079
2.5	.200	.138	.137

For illustrative purposes, Table 2 shows the standard errors of an equating of a 50-item M (Metropolitan Achievement Test) Word Analysis test to a 40-item C (Comprehensive Test of Basic Skills) Reading Vocabulary test. The data were drawn from the Anchor Test Study (Loret, Seder, Bianchini, and Vale, 1974) in which both tests were administered to a group of 1406 sixth-grade students. The resulting bivariate distribution of number-right scores was smoothed by a method described by Lord (1980, Section 17.4). The correlation between M and C was .88. The tabled values were computed from (12), ignoring the smoothing.

The standard deviation of number-right M scores for this group of sixth graders is 11.5. The standard error of measurement for M scores is 2.7. The standard error of equating is much smaller than the standard error of measurement.

Table 3 provides an empirical comparison between equipercentile equating and conventional linear equating. In this case, Form VSA4 of the 90-item SAT Verbal test had been administered to 2665 students, along with an 'anchor test' of 40 verbal items. At a later time, a new, 85-item Verbal form, XSA2, was similarly administered along with the same anchor test to a new group of 2686 students. As part of normal scoring and reporting, Form XSA2 raw ('formula') scores were equated by a standard linear method due to L. R Tucker (Angoff, 1971, Equating Design IV.A.) to the scaled scores on Form VSA4. This equating is shown along with its standard error as determined by the computer program AUTEST (Lord, 1975), in the first three columns of Table 3.

Table 2

Standard Error of Equipercentile Equating, Number-Right Scores,

MAT to CTBS

C Scores	Cumulative Frequency Distribution	Equated M Scores	Standard Error of Equating
37.5	.98	49.3	.17
32.5	.89	45.8	.20
27.5	.76	42.1	.22
22.5	.61	37.6	.26
17.5	.44	31.9	.32
12.5	.26	23.1	.44
7.5	.08	13.8	.36
2.5	.01	8.8	.44

Table 3

Comparison of Linear and Equipercentile Equating for the Verbal Score on Form XSA2, College Board Scholastic Aptitude Test

	Linear (Tucker) Model		Equipercentile Method	
XSA2 formula score	Equivalent scaled score	Standard error	Equivalent scaled score	Standard error
78.1	738	4.07	774	13.47
70.6	685	3.46	722	15.85
64.75	644	3.00	652	10.32
58.9	602	2.56	602	4.97
52.9	559	2.15	558	4.12
47.25	519	1.82	514	3.47
40.1	469	1.54	466	3.44
32.4	414	1.51	417	2.93
25.75	367	1.72	364	3.37
16.1	298	2.28	314	4.07
7.6	238	2.90	242	5.70
-3.75	157	3.80	195	7.85

The equipercentile equating of XSA2 to VSA4 was effected by equating each test to the anchor test independently and then using the rule that scores equated to the same anchor-test score are equated to each other. Thus the equipercentile equating of XSA2 to VSA4 requires two independent equatings of the type treated in Section 3 of this paper. The sampling variances (12) of the two equatings are additive, since they are computed from two different samples of students. The resulting equipercentile equating and standard error are shown in the last two columns of the table.

To put these standard errors into perspective, note that the standard deviation of scaled scores in a group of students is typically about 100. The standard error of measurement of a scaled score is about 30 to 33. The standard errors of equating are mostly small by comparison. The standard errors of the equipercentile equating are double those of the linear equating in the middle of the score range, comparatively larger at the extremes.

Equipercentile equating can be improved by smoothing the empirical frequency distribution of scores before equating. This reduces the sampling errors but may introduce small biases that do not disappear even in very large samples. The sampling error of a smoothed equating could perhaps be determined for a specified smoothing method, but the mathematics would be burdensome.

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