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Use of a Computerized Postural Sway Measurement System for Neurobehavioral Toxicology

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DICK, R. B., A. BHATTACHARYA AND R. SHUKLA. *Use of a computerized postural sway measurement system for neurobehavioral toxicology*. NEUROTOXICOL TERATOL **12**(1) 1–6, 1990.—The study of standing posture has been associated with nervous system functioning for over a hundred years. Measures of human standing ability have attracted some attention as indicators of neurotoxic insult. The use of postural sway measures as subclinical indicators of toxicity has not been regularly incorporated into most neurobehavioral test batteries, but the development of microcomputer-controlled systems offers new possibilities. The mechanisms involved in controlling postural sway are discussed, as well as the various measurement techniques. In addition, studies involving the effects of some neurotoxic agents are cited. A postural sway measurement system that is noninvasive, has 1–2-minute test periods, provides immediate test results, and is relatively free of practice and motivation effects is described. Results present the normative characteristics of the sway parameters, a comparison of three data transformation techniques, and the effects of height and weight on the sway parameters. Power calculations were also performed to estimate the number of subjects needed to detect effects at both the 80% and 90% power levels.

Neurobehavioral Postural sway Stabilometrics Central nervous system

THE maintenance of standing posture has long been associated with assessments of nervous system function (2). Operational terms including postural sway (1,6), stabilometry (20), postural stability (17), human equilibrium (4), postural equilibrium (19), standing steadiness (10) and body sway (14,21) have been used in various reports on human standing abilities. Initially, measures of human standing ability were devoted primarily to the clinical determination of neurological impairment or disease. As tests and measurement techniques have become more refined, however, measures of human-standing ability have been adopted for use in the field of neurotoxicology. The use of postural sway measures as subclinical indicators of toxic insult to the central nervous system is of special interest. Such measures are noninvasive, require little subject preparation and training, have short trial periods, and are minimally affected by motivation or practice (5). They also provide measures of the integration of central and peripheral nervous system processes (20).

The purpose of this paper is to present some parametric results of postural sway indicators from data collected in a controlled laboratory study that used a large number of subjects representing both sexes (8). Specifically, the objectives of this effort were to: 1) calculate means, standard deviations, and summary properties of the sway parameters; 2) determine which measures of postural sway have the potential to be indicators of toxic insult; 3) determine the contributions of height and weight to the parameters of sway; 4) compare data transformation techniques used to normalize the data distributions; and 5) develop estimates of the number of subjects that would be required to detect treatment differences for future use in laboratory and field research. It is the intention of the authors that this paper will provide useful information to other investigators in planning and executing laboratory or field studies using measurements of postural sway as a neurobehavioral performance measure.

From the classic "Romberg Test," first described in 1851 (24), numerous unique devices and measurement techniques have been developed to measure postural sway. These devices and techniques have been summarized in various reviews (1, 3, 20, 22), and include the subjective Romberg observation of sway in the eyes open versus eyes closed comparison, scaled observations of head/body sway, mechanical linkages to the body, video/photographic techniques, accelerometers attached to parts of the body, recordings of eye movement, ultrasound, electromyography, quantitative Romberg measures, and force platforms.

The goal of most researchers has been to develop quantitative approaches. According to Sauter *et al.* (20), three major approaches have been attempted: 1) Direct visual inspection; 2) visual inspection of a transduced signal; and 3) electronic data processing of transduced signals. In present day research, the first two approaches remain viable only when electricity is unavailable, as may be the case in some field testing. With the availability of electronic recorders and microcomputers to collect and analyze data, the third approach is most preferable.

Central nervous system contributions to the control of postural sway come primarily from three major afferent sources: 1) Proprioceptive and kinesthetic; 2) vestibular; and 3) visual (9). These inputs are integrated into a complex pattern of efferent signals that control the antigravity reflexes, passive elastic forces, and tensions that maintain postural stability. Nashner *et al.* (18) has characterized the complex process of maintaining postural equilibrium as a combination of "sensory organization" and "movement coordination." Spectral analysis of stabilogram or accelerometer records from standing subjects reflects oscillations in two distinct frequency ranges: Sway in the 0–1 hertz (Hz) range, and tremor superimposed on the sway in the 1–15 Hz range (20). Anterior-posterior sway generally has a greater magnitude than medial-lateral sway, and closing the eyes increases sway in both directions (19). Sex differences appear to be negligible, but there are some possible age-related effects (6, 17, 23). Sway appears to be independent of height and weight (3,17), but the impact of these variables on all the available measures of sway may not have been adequately investigated (20). Learning and practice effects are reported to be minimal (23).

Visual observation of human standing and locomotion abilities has frequently been part of standard neurological test batteries in field studies involving neurotoxicants (13). In contrast, electronic postural sway measurements have been used primarily in controlled, short-duration exposure studies, or for clinical assessment of individuals exposed to neurotoxicants for extended periods (5,20). Selected studies from the literature that have neurobehavioral implications are summarized below.

Hirasawa (11,12) detected postural sway differences in subjects with short duration exposures to hydrogen sulfide and also in individuals with chronic organosphosphate exposures. Lidegaard *et al.* (16) investigated the effects of the beta-blocker, propanolol, on postural sway and reported impairments with a dose of 10 mg propanolol. Jones *et al.* (14) studied the interaction of ethanol and hyperbaric air and found that ethanol concentrations at 0.77 ml/mg [0.077% blood alcohol concentration (BAC)] increased body sway 30 and 60 min after ingestion. Begbie (2) demonstrated the persistence of ethanol effects three hours after ingestion (blood concentrations at the one hour mark were 60 mg/100 ml, 0.06% BAC). Exercise had little effect on sway measurements, but decreased visual information (closing eyes) increased the mean amplitude of sway scores. Bhattacharya *et al.* (4) reported ethanol effects with blood alcohol concentrations (BAC) as low as 0.015% when the postural equilibrium was primarily controlled by the vestibular system. Franks *et al.* (10) conducted research on the interaction of caffeine and ethanol on standing steadiness. Ethanol ingestion at concentrations that averaged 0.09% BAC significantly increased standing steadiness 40, 100 and 180 min after administration; standing steadiness was not affected by the coadministration of caffeine (300 mg/70 kg).

The effects of solvent exposure on postural sway have also been researched. Savolainen *et al.* (21) exposed subjects to M-xylene (100–400 ppm) for four hours and found no statistically significant increases in postural sway. Similar negative findings have been reported by Dick *et al.* (8) with a 4-hour exposure to either acetone (250 ppm), methyl ethyl ketone (200 ppm), or a combination of acetone (125 ppm) and methyl ethyl ketone (100 ppm).

Recently, Bhattacharya *et al.* (5) have reported the results of a study of children with chronic exposures to lead. The mean blood lead level for the children was 23.4 μg/dl, and the maximum blood lead level incurred during the second year of life was positively related to increases in postural sway.

A feasibility analysis conducted for NIOSH (20) concluded that a force platform system for measuring postural sway was the most promising and versatile of the several techniques available. The major differences between techniques relate to whether the platforms tilt, pivot, or are stationary, and the type of transducers used. Transducers are primarily categorized into three types: Piezoelectric, strain gauge, or inductive (20). For our research, we chose a stationary system with strain gauge transducers. A stationary system was considered easier to install, would be safer and would have portability for use in field studies. Tilting and pivoting systems are more complex and require safety bars, safety belts and more subject preparation time. Strain gauge transducers provide a reliable and durable transducing mechanism at less cost and without the engineering complexity of other alternatives.

METHOD

Subjects and Apparatus

Postural sway data were collected from 135 subjects (68 female, 67 male) ranging in age from 18–32. The data were extracted from a performance test used in a study that involved short-duration exposures to acetone, methyl ethyl ketone, and the combination of these two chemicals (8).

Each subject was given five tests, with four tests administered on one day and one test the following day. Subjects provided a 30-sec sample with eyes open and a 30-sec sample with eyes closed, similar to the "Romberg" test procedures. Sampling rate for the tests was set at 10 hertz (Hz). The eye condition was counterbalanced on each successive test, and the test intervals were separated by two hours. Subjects stood in their stocking feet on the platform, arms at their side, heels together and feet at a 30° separation angle. Feet separation was assured by footprints marked on the platform surface. Since the testing occurred during chemical exposures inside an environmental chamber, two TV cameras, one positioned at eye level and one aimed at the feet, were used to assure proper positioning.

Sway parameter data were collected using an Advanced Mechanical Technology, Inc. (AMTI) computerized biomechanics platform system. The system consists of a six-component, high frequency response (500 Hz), OR6-3 force platform with temperature-compensating, foil-type strain gauge transducers, a SGA6-1 signal conditioner/amplifier, and a Northstar Horizon computer. The force platform rested on the ground. It was sunk into the floor and was bolted to a baseplate anchored in concrete (as a result, the platform was level with the chamber floor). With these procedures, the effects of building vibrations were negligible, and the subjects had no sensation of elevation when standing on the platform.

AMTI-supplied software for data collection and analysis was modified to provide analog-to-digital data printouts from all six recording channels in the platform, including contributions of horizontal forces in the "center of pressure" calculations. The three orthogonal force components (Fx, Fy, and Fz) and the three applied moments (Mx, My, and Mz) used in the "center of pressure" calculations are labeled in Fig. 1.

The modified AMTI software provided 17 summary statistics, and seven were determined to be the best indicators of performance changes. The selections were based on the results of pilot studies by both the first and second authors and from research conducted by the second author (4,5). The primary criteria for selection included sensitivity to ethanol challenges (i.e., change at 0.05 BAC), separation between the eyes open and eyes closed conditions (i.e., eyes closed condition consistently increased the sway measure), and reliability over repeated testing (low within subjects variance). The sway parameters used for detecting performance changes were: Xo, Yo—mean center(s)-of-position pressure relative to the center of the platform; L—length of sway

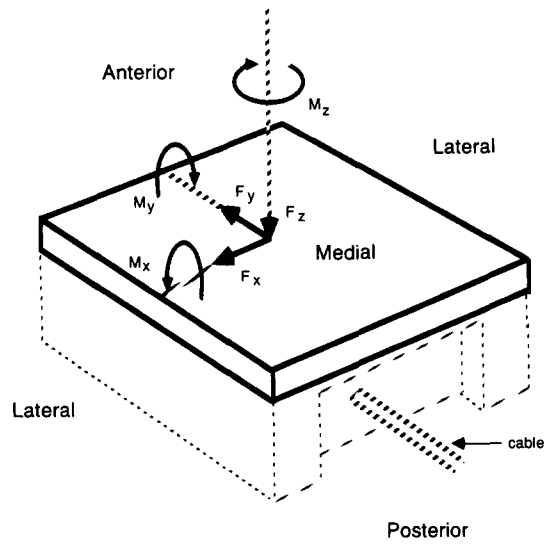

FIG. 1. A view of the force platform showing the reference coordinates used in the center of pressure calculations. Fy = horizontal force; Fx = horizontal force; Fz = vertical force (weight of object); My = movement of applied force about horizontal axes (y); Mx = movement of applied force about horizontal axes (x); Mz = movement of applied force about vertical axes (z).

path (cm); Ao—area included within the sway path (sq cm); Rm—mean radius of sway (cm); Ys—standard deviation of "center of pressure" about the mean y position; and, Vel—mean velocity along the sway path (cm/sec).

RESULTS

The data used in this report come primarily from test periods 1 and 5 in the study by Dick *et al.* (8). These periods did not involve a solvent treatment administration. Data from test period 1 are scores from the subjects' initial tests and are labeled "unpracticed." Data from test period 5, which occurred the day after exposure, represent the fifth test the subjects performed and are labeled "practiced." Analysis of samples of blood and breath taken from subjects indicated there was no treatment carryover from the previous exposure/ingestion. In agreement with other reports (3, 6, 20), there were no consistent statistically significant sex differences in any of the sway parameters, so the data from males and females were combined.

One problem that has been identified by other research using postural sway measurements (20) is the range of individual differences (between subjects variability) in the sway parameters. Similar problems were evident with the raw data collected in this study, so various data transformation techniques were used to determine for each sway parameter which one provided the best fit to normal distribution. The three transformation techniques employed were: 1) Romberg quotient (EO/EC); 2) percent change from baseline; and 3) logarithmic. Table 1 presents the results of this analysis which included all 5 test periods. The logarithmic transformation proved to be the best choice for both the eyes open and eyes closed conditions because this transformation resulted in the best fit for the normal distribution of each sway parameter and also deemphasized the "extremes" and "outliers."

Tables 2 and 3 show the means and standard deviations of the log-transformed scores for the seven sway parameters used by height and weight, respectively. Values from practiced tests (test

TABLE 1

NORMAL DISTRIBUTION FITS* FOR RAW DATA AND DATA TRANSFORMATIONS

Sway Parameter	Xo	Yo	Length	Vel	Ao	Ys	Rm
Data type							
Raw scores							
Eyes open	4	1	2	1	0	0	0
Eyes closed	3	1	0	0	0	0	0
Romberg quotient	0	0	3	1	1	0	1
Percent change†							
Eyes open	0	0	4	4	2	0	0
Eyes closed	0	0	1	0	1	0	2
Logarithmic							
Eyes open	2	3	5	3	4	2	1
Eyes closed	0	4	4	3	5	2	3

*Number of fits for which normal distribution is valid out of the five test periods used ($p>0.10$). For example, 0 under Xo using the Romberg quotient indicates that none of the five test periods distributed normal data for the Xo parameter.

†This transformation was the percent change from baseline, which produces only four scores.

period 5) are used, primarily to simplify the table. Tests for practice effects were not statistically significant. This was indicated by the lack of significant differences between periods one and five, a finding consistent with other studies (17,23). The mean height for the subjects was 171.6 cm, with a range of 167.6 to 177.8 cm. The mean weight for the subjects was 71.98 kg, and the range was 41.6 kg to 111.1 kg. The overall correlation between height and weight was .57 (Pearson r, $p<0.0001$). The scores in Table 2 were divided into three height categories: Low (<167.6 cm); medium (167.6 cm<177.8 cm); high (≥177.8 cm). In Table 3 the scores were divided into three weight categories: Low (<63.5 kg); medium (63.5<77.1 kg); high (≥77.1 kg). Examination of Tables 2 and 3 reveals relatively few marked changes in means and standard deviations between height and weight for the sway measures.

The correlations between height and weight and the sway parameters are presented in Table 4. The log-transformed values are used and bivariate correlations were calculated. Only correlations from the eyes closed test condition are used and, for comparison purposes, both practiced and unpracticed scores are presented because of some minor differences in results. In the eyes open condition, significant correlations ($p<0.05$) occurred only for the Yo measure (both height and weight in both test periods). For the eyes closed condition, the correlation coefficients are, with one exception, less than .30. Roughly half of the sway measures are correlated significantly with height and weight at the $p<0.05$ level. Significant correlations between unpracticed sway scores and height occurred more frequently than significant correlations with weight (4 versus 2), while the opposite was true (4 versus 5) for correlations with practiced scores. Thus, there were more significant correlations with practiced scores than unpracticed scores (9 versus 6). The most consistent significant correlations between unpracticed and practiced tests were between height and the four sway measures of Yo, length, Ao, and velocity. With weight, the only consistent correlations were with Ys, and possibly Rm. In summary, while the contributions of height and weight do not appear to have dramatic effects on sway parameters, there is some interaction. For future research, reliability could be

TABLE 2

POSTURAL SWAY MEASUREMENT MEANS* AND STANDARD DEVIATIONS† BY HEIGHT AND EYE CONDITION‡

	Low (N=42)		Medium (N=52)		High (N=40)	
Height						
Eye Condition	EO	EC	EO	EC	EO	EC
Parameter						
Xo (cm)	1.80	1.76	1.82	1.78	1.82	1.78
	(0.16)	(0.26)	(0.19)	(0.21)	(0.16)	(0.15)
Yo (cm)	1.81	1.96	1.93	2.00	2.11	2.09
	(0.45)	(0.30)	(0.28)	(0.28)	(0.42)	(0.35)
Length (cm)	3.30	3.72	3.37	3.80	3.33	3.89
	(0.25)	(0.29)	(0.30)	(0.36)	(0.33)	(0.33)
Ao (cm^2)	1.79	2.34	1.89	2.38	1.88	2.60
	(0.39)	(0.49)	(0.46)	(0.62)	(0.51)	(0.62)
Rm (cm)	0.45	0.54	0.49	0.54	0.49	0.59
	(0.10)	(0.13)	(0.15)	(0.16)	(0.16)	(0.19)
Ys (cm)	0.41	0.50	0.47	0.50	0.47	0.54
	(0.13)	(0.16)	(0.17)	(0.17)	(0.17)	(0.20)
Vel (cm/sec)	0.66	0.89	0.69	0.93	0.68	1.00
	(0.11)	(0.17)	(0.12)	(0.18)	(0.15)	(0.19)

*Means of transformed scores. Xo − Ln(6.2 + Xo), Yo − Ln(11.6 + Yo), Ao − Ln(1 + Ao), Rm − Ln(1 + Rm), Ys − Ln(1 + Ys), Length − Ln(length), Vel − Ln(1 + Vel).

†S.D.'s are geometric standard deviations.

‡Scores are 30-sec samples for each eye condition in test period 5.

TABLE 3

POSTURAL SWAY MEASUREMENT MEANS* AND STANDARD DEVIATIONS† BY WEIGHT AND EYE CONDITION‡

	Low (N=40)		Medium (N=50)		High (N=43)	
Weight						
Eye Condition	EO	EC	EO	EC	EO	EC
Parameter						
Xo (cm)	1.80	1.83	1.80	1.72	1.84	1.78
	(0.16)	(0.15)	(0.18)	(0.24)	(0.17)	(0.22)
Yo (cm)	1.80	1.98	2.02	2.01	2.00	2.03
	(0.43)	(0.26)	(0.36)	(0.33)	(0.38)	(0.33)
Length (cm)	3.34	3.74	3.34	3.80	3.33	3.85
	(0.25)	(0.31)	(0.28)	(0.32)	(0.35)	(0.37)
Ao (cm^2)	1.85	2.36	1.87	2.43	1.85	2.50
	(0.41)	(0.51)	(0.45)	(0.63)	(0.51)	(0.61)
Rm (cm)	0.46	0.54	0.48	0.56	0.49	0.57
	(0.13)	(0.12)	(0.14)	(0.18)	(0.16)	(0.18)
Ys (cm)	0.42	0.49	0.45	0.52	0.47	0.53
	(0.15)	(0.13)	(0.17)	(0.19)	(0.17)	(0.19)
Vel (cm/sec)	0.68	0. 90	0.67	0.93	0.70	0.99
	(0.11)	(0.18)	(0.12)	(0.19)	(0.15)	(0.19)

*Means of transformed scores. Xo − Ln(6.2 + Xo), Yo − Ln(11.6 + Yo), Ao − Ln(1 + Ao), Rm − Ln(1 + Rm), Ys − Ln(1 + Ys), Length − Ln(length), Vel − Ln(1 + Vel).

†S.D.'s are geometric standard deviations.

‡Scores are 30-sec samples for each eye condition in test period 5.

improved by treating either height or weight, but not both (because they are highly correlated), as a covariate in the data analysis. Based on consistency between the unpracticed and practiced scores, height would be the best choice to correlate with sway measures.

Power analysis calculations were undertaken to develop estimates of sample size requirements for use in future postural sway studies using a data collection system and procedures similar to those described in this paper. These estimates are based on tables and formulae described elsewhere (7). Two tables were developed, one for a two-group-repeated measures study with four test periods, and the other for a four-group-repeated measures study with four test periods. The intent was to determine sample sizes necessary to detect effects using the interactions between the two main effects (such as group × period). Extrapolations can be made, however, for other types of studies using different designs. For example, in a field study with matched exposed subjects and referents, the sample size required would probably be larger because the between-subjects error terms would be used rather than the within-subjects terms.

For interpretation of Tables 5 and 6, the following definitions by Cohen (7) apply. The effect size index (f) represents the standard deviation of the standardized K population means. Three broad f levels are used: Low (f=0.10), medium (f=0.25) and high (f=0.40). The relative difference (d) between the means (relative to the population standard deviation) is defined as the difference between the largest and the smallest of the K means divided by the common standard deviation within the population. The common standard deviation corresponds to the group × period × subjects interaction. The relationship of f and d is represented in the tables as minimum variability (one mean at each end of d, the remaining /K − 2/ means at the midpoint), intermediate variability (the K means equally spaced over d), and maximum variability (all means at the end points of d). Two power levels, 80% and 90%, were used, and the alpha level was 0.05. The values of d for the sway data collected in this study ranged from 0.70 to 0.85, which places the values more or less in the medium (0.25) effect size category. Thus, for 90% power at least

TABLE 4

CORRELATIONS AND *p*-VALUES FOR HEIGHT AND WEIGHT WITH POSTURAL SWAY PARAMETERS IN EYES CLOSED TESTS

	Test Period			
	1		5	
	Height	Weight	Height	Weight
Parameter				
Xo	.07	.03	.04	.02
Yo	.32‡	.24†	.18*	.10
Length	.21*	.06	.19*	.18*
Ao	.22†	.10	.19*	.17*
Rm	.15	.16	.13	.17*
Ys	.10	.20*	.10	.18*
Vel	.22†	.11	.20*	.21*

Values are bivariate correlation coefficients. Test period 1 scores are from unpracticed subjects and test period 5 scores are from practiced subjects.

*$p<0.05$. †$p<0.01$. ‡$p<0.001$.

TABLE 5

ESTIMATES OF SAMPLE SIZE FOR A TWO-GROUP REPEATED MEASURES DESIGN

Effect Size (f)*	0.10 (Low)			0.25 (Med)			0.40 (High)		
Variability†	Mn	Im	Mx	Mn	Im	Mx	Mn	Im	Mx
(d)‡	0.20	0.30	0.40	0.50	0.75	1.00	0.80	1.2	1.6
Power									
80% ($p=0.05$)	N§ = 185			N = 31			N = 13		
90% ($p=0.05$)	N = 235			N = 40			N = 17		

*Standard deviation of K population means is either 0.10, 0.25 or 0.40 as large as the standard deviation of the observations within the populations.

†Variability among cell means: Mn = minimum, Im = intermediate, Mx = maximum.

‡Extracted value based on the relationship between f and the range of standardized means (from Cohen, Table 8.2.1).

§Number of subjects needed to achieve these levels of power for a test of the two factor (group × period) interaction.

40 subjects per cell are needed in a two-group study, and 26 subjects are required for a four-group study.

DISCUSSION

In spite of the fact that previous research (2,20) did not detect significant height and weight correlations with measures of postural sway, this study did identify some mild but significant effects of both height and weight on the sway measures used in the analysis. The detection of height and weight effects were probably due to the larger number of subjects used in this study than in previous studies. The larger subject size provided a better estimate of the true population distribution of postural sway measurements and larger subject sizes also increase the power of tests to detect significant effects (7). The data in this study also support other studies (20) that have reported a wide range of individual differences in sway measurements. To some extent this variability can be reduced through data transformation techniques. The data in this study had the best fit to a normal distribution after logarithmic transformation. Transformations of skewed data that more closely approximate normal distributions also increase the power of statistical tests (15).

This paper described the feasibility of using postural sway analysis techniques in neurobehavioral toxicity testing. The postural sway test could be included in a standard neurological test battery as a replacement for the traditional subjective tests of human standing ability, or it could be added to a neurobehavioral test battery which typically does not include many sensorimotor tests. The system described in this paper is portable and microcomputer controlled. Several problems, however, have been noted with force platform systems. Reliable force platform systems are heavy (>25 kg), and should be mounted in a location where building vibrations are negligible. For postural sway measurements in the field, however, a force platform can be erected and readings taken, to provide sufficient information on whether building vibrations and platform movement would be a problem. Usually the first floor or basement level of a building should suffice for the tests described in this paper. Another problem could be the temperature in the test environment. Although temperature resistant transducers can be used to control the effects of temperature fluctuations, extreme temperature changes, which may be encountered in locations outside the laboratory, may affect force platform readings. An additional problem for some investigators may be financial. The cost of the hardware and software system described here was approximately $30,000. However, the ability to collect quantitative data, the measurement sensitivity, resistance to practice effects, speed at which data can be collected and analyzed, and performance that is free of motivation effects, make postural sway measurement systems an attractive neurobehavioral assessment technique.

TABLE 6

ESTIMATES OF SAMPLE SIZE FOR A FOUR-GROUP REPEATED MEASURES DESIGN

Effect Size (f)*	0.10 (Low)			0.25 (Med)			0.40 (High)		
Variability†	Mn	Im	Mx	Mn	Im	Mx	Mn	Im	Mx
(d)‡	0.20	0.325	0.467	0.50	0.81	1.4	0.80	1.3	2.3
Power									
80% ($p=0.05$)	N§ = 121			N = 21			N = 9		
90% ($p=0.05$)	N = 154			N = 26			N = 11		

*Standard deviation of K population means is either 0.10, 0.25 or 0.40 as large as the standard deviation of the observations within the populations.

†Variability among cell means: Mn = minimum, Im = intermediate, Mx = maximum.

‡Extracted value based on the relationship between f and the range of standardized means (from Cohen, Table 8.2.1).

§Number of subjects needed to achieve these levels of power for a test of the two factor (group × period) interaction.

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