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A Meta-Analysis of the Effects of Calculators on Students' Achievement and Attitude Levels in Precollege Mathematics Classes

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The findings of 54 research studies were integrated through meta-analysis to determine the effects of calculators on student achievement and attitude levels. Effect sizes were generated through Glassian techniques of meta-analysis, and Hedges and Olkin's (1985) inferential statistical methods were used to test the significance of effect size data. Results revealed that students' operational skills and problem-solving skills improved when calculators were an integral part of testing and instruction. The results for both skill types were mixed when calculators were not part of assessment, but in all cases, calculator use did not hinder the development of mathematical skills. Students using calculators had better attitudes toward mathematics than their noncalculator counterparts. Further research is needed in the retention of mathematics skills after instruction and transfer of skills to other mathematics-related subjects.

Key words: Achievement; Attitudes; Calculators; Meta-analysis; Statistical power/effect size

Over the last century, pedagogical methods in mathematics have been in a gradual yet constant state of change. One instigator of change in mathematics classrooms has been technology. Kaput (1992) described the role of technology in mathematics education as "a newly active volcano—the mathematical mountain . . . changing before our eyes, with myriad forces operating on it and within it simultaneously" (p. 515). Technology and the pedagogical changes resulting from it have a decisive impact on what is included in the mathematics curriculum. In particular, what students are taught and how they learn are significantly influenced by the technological forces at work on and within "the mathematical mountain." The situation is compounded by the fact that technology is evolving at a rapid pace. Mathematics educators have the arduous task of keeping up with the advances and incorporating them in lessons and activities. Although this is not easy to do, most educators today cannot imagine a classroom without technology.

The calculator is a technological force that has been a catalyst for lively debate within the mathematics education community during the last 30 years. In the 1970s, the educational relevance of the calculator was a controversial topic. More

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recently, calculators have become commonplace, and discussion has focused around ways to help students achieve maximum benefits from the use of this technology. The highlights of the debate have been outlined in a series of reviews of calculator use research, which I summarize next.

The Calculator Information Center (CIC) at Ohio State University and several independent reviewers (Neubauer, 1982; Parkhurst, 1979; Rabe, 1981; Roberts, 1980; Sigg, 1982) reported on concerns raised by the calculator's introduction into the classroom. The reviews reported on the successes and pitfalls in the implementation of calculator use in American schools (Suydam, 1978, 1979, 1980, 1981, 1982), responded to criticism that the calculator negatively affected results of standardized mathematics achievement tests (Suydam, 1979, 1980), and addressed the possibility that negative calculator effects outweighed the benefits of calculator use (Sigg, 1982). The two most significant findings were that the calculator did not negatively affect student achievement in mathematics and that students' attitudes toward mathematics were not influenced in a positive or negative way by calculator use. The lack of availability of calculator research for educators in the field (Sigg, 1982) and the inadequate use of calculators in the assessment process (Roberts, 1980; Sigg, 1982) were two issues of concern raised by the researchers.

The tone of the debate shifted in the late 1980s with the introduction of the graphing calculator. When the discussion focused on how to incorporate calculators in the most effective manner, the National Council of Teachers of Mathematics (NCTM, 1989) gave the graphing calculator credit for "the emergence of a new classroom dynamic in which teachers and students become natural partners in developing mathematical ideas and solving mathematical problems" (p. 128). Reviews published during this time reported mixed results for calculator use, with positive results becoming more prevalent as time passed, particularly for the development of problem-solving skills (Gilchrist, 1993). Graphing technology was determined to be the central reason for student improvement in three areas: understanding of graphical concepts, the ability to make meaningful connections between functions and their graphs, and enhanced spatial visualization skills (Penglase & Arnold, 1996). The findings relating to students' achievement in mathematics were inconclusive due to the prevalent use of skill-based testing procedures (Gilchrist, 1993; Penglase & Arnold, 1996).

In roughly the same time frame as covered by the calculator reviews summarized above, Hembree and Dessart (1986, 1992) statistically integrated a set of quantitative calculator studies in a comprehensive review through meta-analysis. The results were most significant for calculator use in Grades 3 through 9. Each study included in the meta-analysis involved statistical comparisons of students who used calculators with students who studied the same mathematical material but without the use of calculators. Two important findings were (a) the calculator had no significant effect on students' conceptual knowledge of mathematics and (b) the calculator had a positive influence on students' attitudes toward mathematics.

For computational and problem-solving skills, Hembree and Dessart (1986) separated the studies based on mode of testing and analyzed each group separately.

When calculators were part of the assessment process, the computational and problem-solving skills of students of low or average ability improved. When students in experimental groups were not allowed access to calculators during testing, average students who used calculators during instruction improved in both their computational and problem-solving skills. The only exception was the fourth grade where calculators had a negative effect on computational skills. Overall, the results were encouraging for the role of calculators in mathematics classrooms. The negative result in Grade 4 was a reminder to educators that “calculators, though generally beneficial, may not be appropriate for use at all times, in all places, and for all subject matters” (Hembree & Dessart, 1992, p. 25).

The number of classrooms not incorporating calculators within the mathematics curriculum has diminished significantly in the last few years, and yet the concerns over calculators are still prevalent. On succeeding pages of the May/June 1999 issue of *Mathematics Education Dialogues,* Ralston (1999) encouraged the complete abolishment of paper-and-pencil computations (p. 2), whereas Mackey (1999) recommended the use of calculators be extremely limited (p. 3). Other evidence suggested that educators were most comfortable with the middle ground. For example, in the same edition of *Mathematics Education Dialogues* results from a survey revealed that most educators believed “calculators should be used only after students had learned how to do the relevant mathematics without them” (Ballheim, 1999, p. 6).

To investigate further the effects of calculators, I designed and conducted a meta-analysis for three reasons. First, the literature currently contains over 120 studies featuring a single aspect of this technological force—the effects of calculator use on students in mathematics classrooms. Recent calculator reviews featuring some of these studies (Gilchrist, 1993; Penglase & Arnold, 1996) did not employ inferential methods of evaluation. Thus, a statistical analysis of studies conducted during the last 15 years was warranted. Second, the calculator controversy has not been resolved in the years since the Hembree and Dessart meta-analysis appeared in print, suggesting that research in this area must continue. Third, the mathematics classroom has experienced a variety of changes since the mid-1980s including significant advances in technology, such as the introduction of the graphing calculator, an increase in the level of technological sophistication of the mathematics education population, and documented encouragement by organizations like the NCTM for exploring the pedagogical uses of calculators in classrooms.

Statistical integration of results from the body of studies conducted during this time period is an appropriate way to assess the calculator’s impact on students in the modern classroom. This article addresses the concerns expressed by educators during the last 3 decades through an examination and synthesis of results provided by a set of calculator-based research studies featuring precollege mathematics students. In particular, the analysis covers the calculator’s influence on students’ performance in the following areas: (a) operational, computational, and conceptual skills; and (b) general problem-solving skills including two aspects: the number of problems attempted as the result of having access to a calculator during instruction and the ability to select the appropriate problem-solving strategy. This meta-analysis also considers the calculator's role in the development of student attitudes toward mathematics.

METHOD

This study followed the procedures outlined by Lipsey and Wilson (2001). Other meta-analytical techniques established by experts in the field (e.g., Cooper & Hedges, 1994; Hedges & Olkin, 1985; Hedges, Shymansky, & Woodworth, 1989) were also incorporated as necessary. In the next sections of this article, I present information on various aspects of the meta-analysis.

Constructs and Designs in Calculator-Use Research Studies

Reviews of calculator-based studies over the last 30 years revealed that most research involving use of calculators focused on *changes to student achievement levels* and *attitudes toward mathematics*. These two constructs were featured in Hembree and Dessart's (1986) meta-analysis. Because there has been no change in the focus of recent research reports, the current study featured the same categories and subcategories of achievement and attitude as those outlined in the first meta-analysis. The definitions below originally appeared in the writings of Hembree & Dessart (1986, 1992).

For the achievement construct I sorted the data into three categories: *acquisition*, *retention*, and *transfer* of mathematical skills. Skills acquisition was measured immediately after treatment; skills retention was measured after a predetermined time lapse following treatment; and skills transfer was measured by evaluating the ways that students used the skills in other mathematics-related areas. These skills were further sorted into one of two subcategories, which I call Category I and Category II and explain below.

Category I included skills that I identified as *operational*, *computational*, or *conceptual*. Operational skills were those I identified as the specific skills necessary to solve the mathematical problems on tests of student achievement. If the skill was clearly computational, then I included data from that study in a separate analysis of computational skills, and likewise for studies that involved understanding of mathematical concepts. If an author did not provide information that allowed a skill to be identified as strictly computational or conceptual, then I included the data in the operational skills category.

Category II involved a subcategory of problem-solving skills that were not explicitly stated with the mathematical problems used for assessment. Instead, these were skills that students selected from their mathematical repertoire to solve the verbal problems listed on the achievement tests. Although the number of problems correct (and the number of problems partially correct when partial credit was counted in assessment) was covered by the general category of problem-solving skills, several studies looked at two other aspects of problem solving: *productivity*—

the number of problems attempted by students and *selectivity*—the number of appropriate strategies they used. The selectivity category was somewhat subjective because it was based on the researcher's opinion and expertise as to whether the strategy was appropriate to a particular situation.

The attitude construct included the six attitudinal factors of the Mathematics Attitude Inventory developed through the Minnesota Research and Evaluation Project (Sandman, 1980). The factors are these: (a) attitude toward mathematics, (b) anxiety toward mathematics, (c) self-concept in mathematics, (d) motivation to increase mathematical knowledge, (e) perception of mathematics teachers, and (f) value of mathematics in society. Most attitude-related results involved only the first factor. Studies that either explicitly cited the Mathematics Attitude Inventory or used other available attitude measures like the scales developed by Aiken (1974) and Fennema and Sherman (1976) provided results related to the other five factors. One other factor that was included in this meta-analysis but that Hembree and Dessert (1986, 1992) did not include was students' attitudes toward the use of calculators in mathematics.

In most studies, two groups of students were taught by equivalent methods of mathematical instruction with the treatment group using calculators and the control group having no access to calculators. Several studies compounded the situation by including special curriculum materials designed for calculator use. In both cases, the effects of calculator use were measured by comparing the groups' responses to posttreatment evaluations. The role of the calculator in posttreatment assessment was a significant factor in the meta-analysis reported here. When treatment groups were not allowed access to calculators during testing, the studies were used to analyze student development of mathematical skills during the calculator treatment. When treatment groups had access to calculators during posttreatment evaluations, the studies were used to evaluate the calculator's role in the extension of student mathematical skill abilities after treatment was concluded.

Identification of Studies for the Meta-Analysis

The initial search for studies involved a perusal of the Educational Resources Information Center (ERIC) and the Dissertation Abstracts International (DAI) databases. A manual search of the *Journal for Research in Mathematics Education (JRME), School Science and Mathematics*, and *Educational Studies in Mathematics* from the beginning of 1983 to March, 2002 was used to locate citations and abstracts. I paid particular attention to the annual bibliographies compiled by Suydam and published in *JRME* from 1983 to 1993. When evaluating a study for inclusion in the meta-analysis, I scanned the accompanying bibliography for other inclusion possibilities. The final criteria for inclusion in the meta-analysis were that the study was published between January 1983 and March 2002; it featured the use of a basic, scientific, or graphing calculator; it involved students in a mainstream K–12 classroom; and the report of findings provided data necessary for the calculation of effect sizes. In the case of missing data, I attempted to gather the information from the authors of the original studies. For example, one report omitted class sample sizes and four reports failed to specify whether or not the treatment group had access to calculators during posttreatment evaluations. In all cases, the missing information was successfully obtained before data analysis continued.

The relationship between the characteristics of a study and its results is crucial to meta-analysis. Therefore, quantifying the findings and study characteristics is a significant part of data organization. Once all of the studies are coded, the technique of meta-analysis attempts to determine statistical similarities between research results for the various study characteristics (Glass, McGaw, & Smith, 1981). For the meta-analysis reported here, characteristics of studies featured in the meta-analysis appear in Table 1 and were considered as independent variables. Although some characteristics in the table are self-explanatory, others need elaboration. For the treatment length, *test only* refers to cases where the calculators were a factor only on the test (i.e., available or not available for students to use) without an instructional component beforehand. With regard to curriculum, *special materials* are those designed for instruction with calculators as opposed to *traditional materials* used by both treatment and control groups. *Pedagogical use* refers to using the calculator as an essential element in the teaching and learning of mathematics; *functional use* means that it was used only in activities such as computation, drill and practice, and checking paper-and-pencil work.

Table 1
Characteristics of Studies Featured in the Meta-Analysis

Characteristic	
Publication status	Journal, Dissertation, Other unpublished source
Test instrument	Standardized, Nonstandardized (teacher made)
Educational division	Elementary, Middle School, High School
Ability of students	Mixed, Low, High
Treatment length	Test only; 0–3 weeks, 4–8 weeks, 9 or more weeks
Curriculum	Traditional, Special
Calculator use	Functional, Pedagogical
Calculator type	All types allowed, Basic, Scientific, Graphing
Study design	Random, Nonrandom
Sample size	1–100, 101–200, 210–1000, over 1000

Effect sizes calculated from the numerical outcomes from achievement and attitude assessments were dependent variables. Because the authors of the studies provided means and standard deviations or information from statistical tests based on means and standard deviations, the effect size measure for the meta-analysis was the standardized mean difference—the difference in the experimental and control group means divided by a pooled standard deviation (Lipsey & Wilson, 2001). A positive effect size indicated that the experimental group had a higher mean than the control group for a particular study, whereas a negative effect size implied that the control group performed better than the treatment group; an effect size of zero indicated that there was no difference between the treatment and control groups. Given that Hedges and Olkin (1985) proved that the raw effect size has distribution bias, each raw value was corrected for this problem and the resulting value was used in further analysis. The magnitude of the effect sizes vary according to many different factors, including the researcher's methods and the subject of the research. Mindful of these considerations, Cohen (1988) has established basic guidelines on evaluating the magnitude of effect sizes, with values near 0.2, 0.5, and 0.8 considered to be small, medium, and large, respectively.

With two exceptions, the skill achievement or attitude data gathered from one article was used to generate one effect size for the meta-analysis. Liu (1993) and Pennington (1998) studied groups of students involved in two different treatments with each treatment group being compared to a control group. One group was taught with calculators by traditional instruction methods and the other treatment group was taught with special calculator-related instruction materials. Because each article presented data on two treatment groups that differed significantly in the method of treatment, the resulting effect sizes were not averaged into one value. For these two articles, the two independent groups were considered separate primary studies for the purpose of analysis.

Data Analysis Procedures

Hedge's Q statistic was used to test the homogeneity of a group of effect sizes. This has a chi-square distribution with $k - 1$ degrees of freedom, where k is the number of effect sizes. A set of effect sizes is called homogeneous if each element in the set is an estimate of the population's effect size (Hedges & Olkin, 1985) and the variance in effect sizes is the result of sampling error. Because the potential existed for other sources of variability, a random effects model outlined by Lipsey & Wilson (2001) was used to address the variation among effect sizes.

For a homogeneous set of effect sizes, the population effect size is best estimated by a weighted mean of unbiased effect sizes; therefore, a weighted mean and corresponding 95% confidence interval were generated for each homogeneous set of effect sizes. The mean effect size was determined to be statistically significant (representing a significant difference between the treatment group and the control group's achievement or attitude scores) when the corresponding confidence interval did not contain zero. If the test for homogeneity revealed significant heterogeneity (i.e., $p < .01$), outliers were removed one at a time until a nonsignificant Q was obtained. Although the traditional definition of outlier is a value that is significantly larger or smaller than the others in a data set, outliers in meta-analysis can also result from sample size. For example, if an effect size was generated for a study with a sample size significantly smaller than that in the other studies, then that effect size could be an outlier. In this study, I used a method for identifying outliers developed by Huffcutt and Arthur (1995) that considers effect size value and sample size.

Finally, an analysis of independent variables was conducted to determine the effect of moderator variables on heterogeneity of the effect size data sets and the magnitude of the weighted mean effect sizes. These analyses were conducted with the entire set of effect sizes including those deemed outliers at an earlier stage of analysis.

Description of the Studies

The initial search of the broadly defined category of *calculator-based research in the K– 12 classroom* uncovered 86 studies for the meta-analysis. After evaluating the studies according to the criteria essential for meta-analysis (e.g., presence of a treatment and control group; data necessary for calculating an effect size), 32 studies were eliminated. The final set of 54 studies (see Appendix for the citations) published between January 1983 through March 2002 provided data for 127 effect sizes. Each study was classified according to the characteristics shown in Table 1, and the distribution of the studies according to them appears in Table 2. Looking at the breakdown of studies within a particular characteristic, the numbers do not sum to 54 since several studies provided separate data for more than one classification (e.g., one study provided data on both middle and high school students). Also, the curriculum and calculator use variables were not coded for studies that featured only a test and no instruction with calculators.

Table 2
Distribution of Studies Featured in the Meta-Analysis According to the Set of Characteristics

Characteristic	Number of studies	Characteristic	Number of studies
Publication status		**Curriculum**	
Journal	9	Traditional	41
Dissertation	37	Special	6
Other unpublished source	8	**Calculator use**	
Test instrument		Functional	11
Standardized	24	Pedagogical	36
Nonstandardized	33	**Calculator type**	
Educational division		All types allowed	4
Elementary school	9	Basic	25
Middle school	20	Scientific	3
High school	26	Graphing	22
Ability of students		**Study design**	
Mixed	46	Random	44
Low	2	Nonrandom	10
High	7	**Sample size**	
Treatment length		1–100	28
Test only	7	101–200	18
0–3 weeks	17	201–1000	4
4–8 weeks	9	Over 1000	4
9 or more weeks	21		

Overall, 85% of the studies appeared either as journal articles, dissertations, or masters theses. Of the remaining studies, one was an unpublished report and the other eight were ERIC documents. A variety of standardized tests were used to assess achievement (e.g., Scholastic Aptitude Test, Iowa Test of Basic Skills), and nonstandard methods of assessment used by some researchers were teacher or researcher designed tests.

With regard to grade level, roughly two thirds of the reports featured more than one grade level, and as a consequence it was not possible to analyze the data by individual grades. Instead, I sorted the studies into *educational divisions*—elementary, middle, and high school. The elementary grades were represented by the fewest number of studies. Nearly 70% of the studies involved at least one of grades 8 through 12. Based on this distribution, inferences drawn from this meta-analysis are best applied to mathematics students in higher grades.

The length of calculator treatment ranged from test only (i.e., the studies involved a test with no instructional use of calculators before testing) to 650 days (i.e., 3 1/2 school years). The duration of the treatment phase exceeded 30 days for nearly 60% of the studies. Only three studies evaluated students after a predetermined retention period ranging from 2 to 12 weeks.

Random assignment of classes of students to the calculator treatment was used in 81% of the studies. In the remaining studies it was either clear that assignment to treatment was not random or the study design was not obvious from reading the article. Although a randomized, strictly controlled study is the ideal, this type of study is not always possible in educational research. Studies using random and nonrandom assignment were included in the meta-analysis. The study design variable was coded to determine whether or not including nonrandomized studies influenced the meta-analytical findings (Lipsey & Wilson, 2001).

Combined sample sizes of treatment and control groups ranged from 14 to 48,081. Eighty-five percent of the studies were conducted with samples of 200 participants or less. Four calculator studies were conducted with over 4,000 students participating.

RESULTS

The sections that follow present results from the meta-analysis and interpretations of the findings. For comparison purposes, analysis of heterogeneous sets of effect sizes was conducted twice: (1) with all of the effects and (2) with outliers removed yielding a homogeneous set of effects. The tables provide the 95% confidence intervals that were used to determine the statistical significance of g, the corresponding weighted mean effect size. Hedges Q statistics, used to determine the homogeneity of each set of effect sizes, are also included in these tables. For the skill data that was heterogeneous in the first round of the analysis, I included an independent variable analysis to gain information about the heterogeneity of the data. The results for student attitudes and the corresponding independent variable analysis conclude the results section.

Effect Sizes

Table 3 contains the number of effect sizes gathered for each achievement construct (acquisition, retention, transfer) and category of skills analyzed in this study. Each number in the table represents comparison of achievement data from treatment and control groups. The results are organized according to method of testing—with or without calculators.

Table 3
Number of Effect Sizes for the Achievement and Skill Constructs, Their Categories, and Calculator Use in Testing

	Testing without calculators			Testing with calculators			
	Acquisition	Retention	Transfer	Acquisition	Retention	Transfer	Total
			Category I skills				
Operational	15	0	0	25	2	1	43
Computation	15	1	0	12	2	0	30
Concepts	8	0	0	11	0	0	19
			Category II skills				
Problem solving	7	0	0	14	2	1	24
Productivity	0	0	0	1	0	0	1
Selectivity	3	0	0	6	1	0	10
Total	48	1	0	69	8	2	127

With regard to the numbers within Table 3, there were 15 effect sizes used to analyze student acquisition of operational skills. These values were gathered from 15 studies that provided data on student acquisition of operational skills in which the skills were not strictly computational or conceptual, but instead was a composite of the two. Each report contained quantitative data on the comparison of a treatment and control group in which the treatment group had access to calculators during instruction but not during testing. Similarly, the results outlined below on student acquisition of problem-solving skills when calculators were part of testing and instruction are based on the analysis of 14 effect sizes.

The general category of operational skills contains the most information for analysis with 43 effect sizes across both testing conditions. Results on productivity are not provided since only one study provided data on this problem-solving skill. Sixty-nine effect sizes were available to analyze skills acquisition when calculators were part of testing as well as instruction. The results of the acquisition of operational and problem-solving skills when calculators were not part of the testing process are based on 48 effect sizes.

Although technically an analysis can be conducted with as few as two effect sizes, the results from such a small number of studies are not a strong reflection of the population under consideration. Therefore, I chose to analyze only those categories with three or more effect sizes. The 54 studies included in this meta-analysis did not provide much information on skills retention and transfer so this meta-analysis does not provide information on these two aspects of achievement.

Effect Size Findings for Acquisition of Skills—Testing Without Calculators

Table 4 includes the results from an analysis of the achievement construct of acquisition of operational and problem-solving skills in testing situations that did not permit the use of calculators. The results showed that there were two significant findings in which the 95% confidence interval did not contain zero: operational skills (.03, .31) and selectivity skills (.15, .44). Because the *Q* statistic was significant for operational skills (indicating that the data set was not homogeneous), I conducted further analysis, which resulted in the removal of an outlier and in *Q* no longer being statistically significant. The operational skills weighted mean effect size (g = .17) was slightly smaller (g = .14) after this was done, resulting in a new confidence interval of (.01, .38) that also did not contain zero. These findings suggest that for assessments of operational skills and problem-solving selectivity skills in which calculators were not allowed during testing, students using calculators *during instruction* performed better than the control group. For problem-solving selectivity skills, the mean effect (g = .30) was based on three studies that assessed the ability of students using calculators to select the appropriate problem-solving strategies, and consequently this result should be interpreted with caution.

Table 4
Results from the Analysis of Acquisition of Skills—Testing Without Calculators

Skill Type	k	g	CI	U_3	Q	N_e	N_c
Operational skills							
All studies	15	.17	(.03, .31)	57	29.5*	1069	1065
Outliers removed	14	.14	(.01, .38)		25.5	1044	1047
Computational skills							
All studies	15	.03	(–.14, .20)		32.1*	843	886
Outliers removed	14	–.02	(–.16, .11)		17.7	763	786
Conceptual skills							
All studies	8	.05	(–.20, .29)		28.1*	650	715
Outliers removed	7	–.05	(–.19, .09)		7.3	590	655
Problem-solving skills							
All studies	7	.16	(–.01, .32)		5.2	287	273
Selectivity skills							
All studies	3	.30	(.15, .44)	62	1.0	346	420

Note. k = number of studies; g = weighted mean effect size; CI = 95% confidence interval for g; U_3 = percentage of area below g on the standard normal curve (reported only for CIs that do not contain zero); Q = homogeneity statistic; N_e = combined experimental group sample size; N_c = combined control group sample size.
* $p < .01$

Both of these values (g = .17 and g = .30) are considered to be small according to the guidelines for evaluating the magnitudes of effect sizes. The U_3 statistic was calculated for each weighted mean effect size in order to present a clearer interpretation of each value. The U_3 statistic converts an effect size to the percentage of area falling below the given effect size value on the standard normal curve (Cohen, 1988). U_3 is the percentage of students in the treatment group who scored higher than the median score of the control group while, based on the definition of median, 50% of students in the control group scored higher than the median score of the control group. For the weighted mean effect sizes for these constructs, the U_3 statistics are 57 for operational skills and 62 for selectivity skills. The value 57 means that while 50% of students in the control group scored higher than the median on achievement tests of operational skills, 57% of students using calculators during instruction scored higher than the median score of the control group on achievement tests of operational skills. Based on the writings of Cohen (1988), another interpretation is the average student who had access to a calculator during instruction had a mathematics achievement score that was greater than 57% of the students who did not have access to calculators during instruction. The U_3 statistic for problem-solving selectivity skills was slightly higher at 62, but was based on a small number of studies.

The computational, conceptual, and problem-solving skills categories did not yield statistically significant results because their confidence intervals contained zero. Because the data sets for the computational and conceptual skills constructs were not homogeneous in the initial stage of analysis, the outlier analysis was conducted. However, even after removing outliers, the confidence intervals for the weighed mean effect sizes still contained zero. Therefore, students who used calculators during instruction did not perform significantly higher on tests of mathematical achievement without calculators than their noncalculator-use counterparts. Whereas students did not benefit from the use of calculators when developing computational and conceptual skills, their abilities were also not hindered by calculator use.

The problem-solving data set was homogeneous after the first stage of analysis, so it was not necessary to run the outlier analysis. Although the lower value of the confidence interval is negative, the value is small enough to be considered zero. Therefore, the students in the treatment and control groups were not significantly different on assessment measures of problem-solving skills.

Effect Size Findings for Acquisition of Skills—Testing With Calculators

As shown in Table 5, statistically significant weighted mean effect sizes were generated for four of the five construct categories in which calculators were allowed during testing. Selectivity was the only one that did not have a significant effect size. Because the Q statistic was significant for these four categories, outlier analysis was conducted. Three constructs, operational skills ($g = .38$), computational skills ($g = .43$), and problem-solving skills ($g = .33$), were slightly affected by the removal of outliers resulting in g values of .32, .41, and .22, respectively. However, these changes in effect size magnitude were minimal, and the resulting effect size values for all four constructs can be considered as small to medium.

Table 5

Results from the Analysis of Acquisition of Skills—Testing With Calculators

Skill Type	*k*	*g*	CI	U_3	*Q*	N_e	N_c
Operational skills							
All studies	25	.38	(.28, .48)	65	243.1*	32892	31397
Outliers removed	19	.32	(.21, .42)		30.6	3589	3534
Computational skills							
All studies	13	.43	(.18, .67)	67	63.2*	3277	2123
Outliers removed	11	.41	(.23, .59)		24.7	3213	2069
Conceptual skills							
All studies	11	.44	(.20, .68)	67	60.4*	3100	2444
Outliers removed	8	.44	(.19, .69)		17.1	2653	2090
Problem-solving skills							
All studies	14	.33	(.12, .54)	63	41.6*	3226	2089
Outliers removed	12	.22	(.01, .43)		19.9	400	404
Selectivity skills							
All studies	6	.20	(–.01, .42)		2.4	153	189

Note: *k* = number of studies; *g* = weighted mean effect size; CI = 95% confidence interval for *g*; U_3 = percentage of area below *g* on the standard normal curve (reported only for CIs that do not contain zero); *Q* = homogeneity statistic; N_e = combined experimental group sample size; N_c = combined control group sample size.

* $p < .01$

The U_3 statistic was calculated to interpret the mean effect sizes for each construct category. Studies of computational and conceptual skills generated the highest value (67); the values for the other two constructs were in the same middle 60s range. With respect to the skills necessary for understanding mathematics concepts and computation, 67% of students using calculators during instruction scored higher than the median score of the control group on mathematics achievement tests. Similar statements can be made comparing more than 60% of students using calculators with their control group counterparts in terms of operational skills and problem-solving skills.

Six studies of problem-solving selectivity skills in which calculators were allowed during testing yielded a weighted mean effect size ($g = .20$) that was not statistically significant. Therefore, development of the skills necessary to select appropriate problem-solving strategies was neither helped nor hindered by calculator use.

All of the weighted mean effect sizes generated for the constructs under both testing conditions were relatively small. However, Cohen (1988) states that due to the circumstances under which these studies were conducted this is to be expected: “When phenomena are studied which cannot be brought into the laboratory, the influence of uncontrollable extraneous variables (‘noise’) makes the size of the effect small relative to these (makes the ‘signal’ difficult to detect)” (p. 25). It should also be noted that when comparing the two methods of assessment, the studies in which calculators were allowed during testing yielded more statistically significant results than the studies in which calculators were not part of the assessment process.

For the results outlined above that were based on homogeneous data sets in the first stage of analysis, it can be assumed that the weighted mean effect size was the best estimate of the population represented by the data. For studies that did not allow calculators during testing, the problem-solving skills category and the selectivity skills category were homogeneous in the first stage of analysis. This was also true for selectivity skills when calculators were part of instruction and testing. Therefore, the weighted mean effect sizes and corresponding confidence intervals for these constructs adequately represented the population from which the data came.

The weighted mean effect size was not the best estimate of the population (Lipsey & Wilson, 2001) for the sets of effect sizes that were heterogeneous in the first stage of analysis (i.e., operational skills, computational skills, and conceptual skills when calculators were not included in testing; operational skills, computational skills, conceptual skills, and problem- solving skills when testing included calculators) and the difference was likely based on a study's characteristics (i.e., independent variables). In order to determine the influence of independent variables on the heterogeneity of effect sizes in each achievement construct, I conducted an analysis of moderator variables. This was done to gain insight into the reasons a set of effects was heterogeneous and to help explain the influence of the coded independent variables on the student achievement constructs under consideration.

Analysis Using Moderator Variables

In the moderator variable analysis, all characteristics except for sample size listed in Table 1 were included with some merged in order to produce meaningful comparisons. The sections that follow present results for the independent variables that yielded significant results; for the variables that did not, such results are not reported. The significance level, $p < .01$, was used to determine whether there was a significant difference in effect size magnitudes for each independent variable. Ninety-five percent confidence intervals were used to determine the statistical significance of g, the corresponding weighted mean effect size.

Testing without calculators. Because the initial test for homogeneity for problem-solving skills and selectivity revealed a homogeneous set of effect sizes (see Table 4), an independent variable analysis was not conducted for this set of data. Instead, the focus for this part of the study was on the skill type variables on operational, computational, and conceptual. The results from this analysis appear in Table 6.

The data in the top portion of Table 6 show that for operational skills, only one independent variable—treatment length—produced significant differences for effect size magnitudes across three treatment categories: 0–3 weeks, 4–8 weeks, and 9 or more weeks. Treatment length ($Q_B = 14.5$, $p < .01$) resulted in a negative weighted mean effect size ($g = –.17$) for studies conducted over a 4–8 week treatment period. However, the value was not significantly different from zero based

Table 6

Moderator Variable Analysis of Skill Effects—Testing Without Calculators

Operational Skills					
Variable	*k*	*g*	CI	Q_W	Q_B
Treatment length					
0–3 weeks	4	.31	(.14, .48)	1.8	14.5*
4–8 weeks	3	–.17	(–.36, .02)	1.5	
9 or more weeks	8	.24	(.05, .42)	11.7	

Computational Skills					
Variable	*k*	*g*	CI	Q_W	Q_B
Treatment length					
0–3 weeks	3	.14	(–.51, .78)	7.2	13.4*
4–8 weeks	3	–.25	(–.49, –.01)	1.9	
9 or more weeks	9	.06	(–.08, .20)	9.6	

Conceptual Skills					
Variable	*k*	*g*	CI	Q_W	Q_B
Educational division					
Elementary school	4	–.06	(–.29, .18)	5.5	16.5*
Middle school	2	.52	(–.26, 1.29)	5.8	
High school	2	–.15	(–.38, .09)	0.2	
Treatment length					
0–3 weeks	3	.26	(–.48, 1.00)	17.4*	10.3*
4–8 weeks	2	–.29	(–.55, –.04)	0.3	
9 or more weeks	3	.08	(–.06, .22)	0.2	
Calculator use					
Functional	4	–.21	(–.42, .01)	2.3	7.1*
Pedagogical	4	.21	(–.15, .57)	18.7*	

Note. *k* = number of studies; *g* = weighted mean effect size; CI = 95% confidence interval for *g*; Q_W= homogeneity statistic; Q_B= difference between contrasted categories

* $p < .01$

on the confidence interval values. Positive values were generated for calculator treatments of operational skills lasting 0–3 weeks ($g = .31$) and 9 or more weeks ($g = .24$); in both cases, the weighted mean effect sizes were significantly larger than zero. Therefore, the operational skills of students using calculators less than or equal to 3 weeks or 9 or more weeks improved. Because the result for 9 or more weeks was based on eight studies, this result was the most credible of the results presented for the analysis by treatment length.

As shown in the middle portion of Table 6, treatment length ($Q_B = 13.4$, $p < .01$) also produced a significant result for effect sizes resulting from computational skills assessments in which calculators were not part of testing. The 0–3 weeks and 9 or more weeks categories yielded positive weighted mean effect sizes, but the values were not significantly different from zero. Therefore, for these treatment lengths, students using calculators during instruction but not during testing were neither helped nor hindered by calculator use. The negative weighted mean effect size for studies conducted over a 4–8 week treatment period indicated that students not using calculators during instruction outperformed their calculator counterparts on tests of computational skills.

The conceptual skills construct (see the lower portion of Table 6) resulted in significant differences for three independent variables: educational division, treatment length, and calculator use. With respect to educational division ($Q_B = 16.5$, $p < .01$), the weighted mean effect sizes generated for elementary school ($g = -.06$), middle school ($g = .52$), and high school studies ($g = -.15$) did not correspond to a significant difference in the conceptual skills assessment outcomes for calculator and noncalculator students. With respect to treatment length, the results were similar to those reported for the computational skills construct. The 0–3 weeks and 9 or more weeks time frames yielded positive weighted mean effect sizes that were not significantly different from zero. Therefore, for these two treatment lengths, students using calculators during instruction on conceptual skills were neither helped nor hindered by calculator use. The 4–8 week time frame resulted in a negative weighted mean effect size, suggesting that students who did not have access to calculators outperformed students who used calculators during lessons on conceptual skills. The magnitude of effect sizes for the conceptual skills construct also differed significantly with respect to the calculator use variable ($Q_B = 7.1$, $p < .01$). The weighted mean effect sizes for functional use and pedagogical use were small, and neither value was significantly different from zero.

Testing with calculators. This section presents results of an analysis of operational skills, computational skills, and conceptual skills by independent variable for studies in which the calculators were part of testing. There was no single independent variable for which a significant difference existed across all three constructs. The operational skills and conceptual skills constructs were the two areas most affected by the variables that were featured in this analysis.

The top portion of Table 7 contains the results for the operational skills analysis of the independent variables. The analysis revealed that the magnitude of effect sizes differed significantly with respect to publication status ($Q_B = 140.6$, $p < .01$). The weighted mean effect size was smallest for studies presented as other unpublished documents such as those from ERIC ($g = .27$). The value generated from dissertations ($g = .31$) was slightly larger. The weighted mean effect size for studies that appeared as journal articles ($g = .50$) was moderate in size. All three values were statistically significant in favor of students who had access to calculators during instruction.

Based on the significant difference in the test instrument variable ($Q_B = 18.3$, $p < .01$), nonstandardized tests yielded a slightly larger ($g = .44$) weighted mean effect size when compared with standardized tests ($g = .32$). However, both values were moderate in size but statistically significant. Therefore, students taking standardized and nonstandardized teacher-made tests of operational skills benefited from calculator use during instruction.

The educational division variable also had a significant influence on the magnitude of effect sizes ($Q_B = 17.1$, $p < .01$) but only in the middle school and

Table 7
Moderator Variable Analysis of Operational and Computational Skill Effects—Testing With Calculators

Operational Skills					
Variable	k	g	CI	Q_W	Q_B
Publication status					
Journal	7	.50	(.36, .65)	29.0*	140.6*
Dissertation	12	.31	(.08, .54)	31.9*	
Other	6	.27	(.13, .41)	41.6*	
Test instrument					
Standardized	9	.32	(.18, .46)	177.2*	18.3*
Nonstandardized	16	.44	(.24, .63)	47.7*	
Educational division					
Elementary school	1	.48	(.17, .78)	0.0	17.1*
Middle school	7	.57	(.15, .98)	34.1*	
High school	17	.32	(.21, .44)	192.0*	
Ability level					
Mixed	22	.35	(.24, .45)	224.9*	14.1*
High	3	.69	(.29, 1.10)	4.2	
Treatment length					
Test only	6	.29	(.15, .43)	148.8*	28.3*
0–3 weeks	8	.47	(.11, .82)	33.8*	
4–8 weeks	3	.34	(–.11, .79)	6.0	
9 or more weeks	8	.49	(.18, .81)	26.3*	
Calculator type					
All	4	.25	(.10, .41)	144.0*	28.5*
Basic/scientific	8	.55	(.20, .90)	31.1*	
Graphing	13	.40	(.19, .60)	39.5*	
Study design					
Random	21	.33	(.23, .44)	217.6*	19.9*
Nonrandom	4	.68	(.35, 1.01)	6.2	

Computational Skills					
Variable	k	g	CI	Q_W	Q_B
Publication status					
Journal	3	.82	(.26, 1.73)	23.3*	19.6*
Dissertation	9	.18	(–.12, .48)	20.3*	
Other	1	.96	(.63, 1.28)	0.0	
Study design					
Random	10	.24	(.02, .47)	28.7*	27.6*
Nonrandom	3	1.18	(.57, 1.78)	6.9*	

Note. k = number of studies; g = weighted mean effect size; CI = 95% confidence interval for g; Q_W = homogeneity statistic; Q_B = difference between contrasted categories
* $p < .01$

high school. The weighted mean effect size for studies at the middle school level ($g = .57$) was larger than the effect size for studies at the high school level ($g = .32$). For both divisions, the results were statistically significant in favor of students using calculators during instruction.

The significant difference in effect size magnitude with respect to ability level ($Q_B = 14.1$, $p < .01$) resulted from 3 studies of high ability students that were separated from the remaining 22 studies conducted in mixed ability classrooms. There were no studies of operational skills that were conducted solely with low ability students. The weighted mean effect size for the high ability studies ($g = .69$) was in the high range, while the corresponding statistic for the mixed ability studies ($g = .35$) was moderate in size. Both values were statistically significant.

The analysis of independent variables revealed that the magnitude of the effect sizes differed significantly with respect to treatment length ($Q_B = 28.3$, $p < .01$). Unlike the similar analysis described above for studies in which calculators were not allowed during testing, there were no negative weighted mean effect sizes for any of the four treatment length categories. The effect size value for studies featuring only a test ($g = .29$) was small, whereas the weighted mean effect sizes for the 0–3 weeks and 9 or more weeks categories fell in the moderate range. The results for the test only, 0–3 weeks, and 9 or more weeks categories were statistically significant in favor of students using calculators. For studies conducted over a 4–8 week time frame, students were neither helped nor hindered by the inclusion of calculators in testing and instruction.

Calculator type ($Q_B = 28.5$, $p < .01$) also revealed significant differences in effect size magnitudes, and all three results were significantly different from zero. Four studies allowed students to use any type of calculator (basic, scientific, or graphing) and did not feature any form of mathematics instruction. Each study was a comparison of students taking a test with access to calculators and students taking the same test without access to calculators. The studies with basic or scientific calculators yielded a higher weighted mean effect size ($g = .55$) when compared to the effect size for studies featuring the graphing calculator ($g = .40$). The results for this independent variable reveal that for all types of calculators, students using calculators during testing and instruction performed better than their noncalculator counterparts on tests of operational skills.

Lastly, the magnitude of effect sizes for the operational skills construct differed significantly with respect to study design ($Q_B = 19.9$, $p < .01$). The four studies in which the treatment group was not selected by random assignment generated a relatively large weighted mean effect size ($g = .68$). The studies in which random assignment was used resulted in a moderate effect size ($g = .33$). Both values represent a statistically significant difference between assessment results of students using calculators during instruction and students with no access to calculators during instruction. Due to selection bias in the nonrandomized design (Lipsey & Wilson, 2001), it appears that the nonrandomized studies overestimated the magnitude of the effect of calculators on operational skills.

The lower portion of Table 7 shows that significant differences in effect size magnitudes for two independent variables resulted from the analysis of the computational skills construct. For publication status ($Q_B = 19.6$, $p < .01$), the result was similar to the one reported above for operational skills. The weighted mean effect size for studies appearing in journals ($g = .82$) was fairly large. The effect size for dissertations ($g = .18$) was not significantly different from zero, whereas the journal result was statistically significant in favor of the calculator group. Study design also revealed significant differences ($Q_B = 27.6$, $p < .01$) in the magnitude of effect sizes. The three studies conducted without random assignment to the treatment group yielded a large weighted mean effect size ($g = 1.18$). Based on the size of this value, the nonrandomized studies appear to overestimate the overall effect of calculators on computational skills. The effect size for studies conducted with random assignment ($g = .24$) was smaller, but both values were significantly different from zero.

The upper portion of Table 8 contains the results of the independent variable analysis for conceptual skills and shows significant differences in effect size magnitudes for five variables. For test instrument ($Q_B = 7.5$, $p < .01$), the studies using nonstandardized tests ($g = .60$) yielded a weighted mean effect size that was statistically significant. Therefore, students who took teacher-made tests of conceptual skills benefited from calculator use. The result for standardized tests ($g = .16$) was not statistically significant. With respect to educational division ($Q_B = 13.0$, $p < .01$), the middle school division generated the largest weighted mean effect size ($g = .70$) followed by the high school division ($g = .43$). The effect size for the elementary division ($g = –.14$) was based on only two studies and was not statistically significant. The middle and high school values were significantly different from zero.

A significant difference in effect size magnitude was found for ability level ($Q_B = 11.5$, $p < .01$). The studies that featured high ability students were separated from the studies conducted in mixed ability classrooms. The result was a higher weighted mean effect size for the high ability classes ($g = .84$), but the value was not significantly different from zero. For calculator use ($Q_B = 17.5$, $p < .01$), the studies in which the calculator had a functional role yielded a smaller effect size value ($g = .12$) when compared with the studies in which the calculator had a pedagogical role ($g = .69$). The effect size for the functional studies was not statistically significant in favor of the students using calculators but the value for pedagogical studies revealed that students who used calculators outperformed their noncalculator counterparts on assessments of conceptual skills. A significant difference in effect size magnitude was generated by calculator type ($Q_B = 9.7$, $p < .01$). The weighted mean effect size ($g = .69$) for the graphing calculator studies was in the high range. The effect size value for the studies featuring basic and scientific calculators ($g = .13$) was not statistically significant.

The lower portion of Table 8 contains the independent variable analysis for problem-solving effect sizes from studies in which calculators were allowed during testing. Significant differences in effect size magnitudes resulted from analysis of ability level ($Q_B = 12.0$, $p < .01$) and calculator type ($Q_B = 12.9$, $p < .01$). The high ability category contained only one effect size. The low ability category, consisting of two effect sizes, yielded a negative weighted mean effect size ($g = –.18$) but the result was not statistically significant for either the calculator or the noncalculator group. The mixed ability studies generated a moderate effect size value ($g = .43$)

Table 8
Moderator Variable Analysis of Conceptual and Problem-Solving Skill Effects—Testing With Calculators

Conceptual Skills

Variable	k	g	CI	Q_W	Q_B
Test instrumen					
Standardized	3	.16	(–.12, .44)	18.2*	7.5*
Nonstandardized	8	.60	(.16, 1.05)	34.7*	
Educational division					
Elementary school	2	–.14	(–.42, .15)	0.1	13.0*
Middle school	5	.70	(.13, 1.27)	34.9*	
High school	4	.43	(.03, .82)	12.6*	
Ability level					
Mixed	8	.29	(.06, .52)	32.6*	11.5*
High	3	.84	(–.04, 1.71)	16.2*	
Calculator use					
Functional	2	.12	(–.05, .29)	0.5	17.5*
Pedagogical	7	.69	(.23, 1.16)	31.0*	
Calculator type					
Basic/scientific	4	.13	(–.14, .40)	19.7*	9.7*
Graphing	7	.69	(.23, 1.15)	31.0*	

Problem-Solving Skills

Variable	k	g	CI	Q_W	Q_B
Ability level					
Mixed	11	.43	(.20, .65)	29.6*	12.0*
Low	2	–.18	(–.59, .23)	0.0	
High	1	.15	(–.31, .62)	0.0	
Calculator type					
Basic/scientific	11	.23	(–.01, .47)	19.9	12.9*
Graphing	3	.61	(.12, 1.10)	8.9	

Note. k = number of studies; g = weighted mean effect size; CI = 95% confidence interval for g; Q_W = homogeneity statistic; Q_B = difference between contrasted categories
* $p < .01$

that was significantly different from zero. Therefore, the problem-solving skills of students in mixed ability classrooms improved from calculator use during testing and instruction. With regard to the calculator type variable, the studies that featured the graphing calculator yielded a weighted mean effect size (g = .61) in the moderate to high range that was statistically significant in favor of the students using calculators. The studies that involved a basic or scientific calculator generated a relatively small effect size value (g = .23) that did not significantly favor the calculator group.

Findings Regarding Student Attitudes

Table 9 summarizes the meta-analytical findings regarding the attitude constructs. The data set for the attitude toward mathematics construct was heterogeneous at the initial stage of analysis. Therefore, just as with the skills constructs, analysis was conducted with all studies and then after the removal of outliers. Due to insufficient data, inferential statistics could not be generated for four of the categories: anxiety toward mathematics, motivation to learn mathematics, attitude toward mathematics teachers, and students' perceptions of the value of mathematics in society.

Table 9
Results from the Analysis of Attitude Constructs

Construct	k	g	CI	U_3	Q	N_e	N_c
Attitude toward mathematics							
All studies	18	.32	(.07, .58)	63	134.5*	1366	1286
Outliers removed	12	.20	(.01, .40)		22.8	491	457
Self-concept in mathematics							
All studies	4	.05	(–.06, .16)		2.6	706	631
Attitude toward use of calculators in mathematics							
All studies	3	.09	(–.19, .36)		3.7	645	556

Note: k = number of studies; g = weighted mean effect size; CI = 95% confidence interval for g; U_3 = percentage of area below g on the standard normal curve (reported only for CIs that do not contain zero); Q = homogeneity statistic; N_e = combined experimental group sample size; N_c = combined control group sample size.

* $p < .01$

The data for the students' attitudes toward mathematics construct yielded a statistically significant weighted mean effect size ($g = .32$). The value was slightly smaller after the removal of outliers. This weighted mean effect size means that on attitude survey instruments, the students using calculators during instruction reported a better attitude toward mathematics than the students who did not use calculators. This weighted mean effect size is in the small to moderate range. The U_3 statistic for this value was 63. One interpretation of this statistic is that the average student who had access to a calculator during instruction reported an attitude toward mathematics that was better than 63% of the students who did not have access to calculators during instruction.

Small weighted mean effect sizes were generated for students' self-concept in mathematics ($g = .05$) and attitudes toward use of calculators in mathematics ($g = .09$). Both of these effect size values were based on a small number of studies. Neither value was significantly different from zero. Therefore, students who used calculators during instruction and students who did not use calculators during instruction reported similar opinions on questions regarding these attitude constructs.

Due to the heterogeneity of effect sizes for the attitude towards mathematics construct, an analysis of independent variables was conducted, and the results are presented in Table 10. Significant differences in the magnitudes of weighted mean effect sizes are reported for seven variables. Regarding publication status ($Q_B = 11.7$, $p < .01$), one journal was combined with the results for dissertations, and the weighted mean effect size (g = .35) was small to moderate. The value was significantly different from zero. The effect size value for the ERIC documents or other unpublished documents was negative (g = –.01) but close to zero and not statistically significant in favor of students in the control group. The test instrument variable ($Q_B = 22.5, p < .01$) yielded a weighted mean effect size for studies using standardized tests (g = .32) slightly larger than the value for studies using nonstandardized tests (g = .28). The result for standardized tests is statistically significant in favor of students who had access to calculators during instruction.

Table 10
Moderator Variable Analysis—Attitude Construct

Variable	k	g	CI	Q_W	Q_B
Publication status					
Journal/dissertation	16	.35	(.09, .62)	106.5*	11.7*
Other	2	–.01	(–1.48, 1.46)	16.3*	
Test instrument					
Standardized	10	.32	(.05, .59)	49.8*	22.5*
Nonstandardized	8	.28	(–.23, .78)	62.2*	
Educational division					
Elementary school	4	.15	(–.19, .49)	4.2	10.7*
Middle school	7	.28	(–.12, .69)	64.1*	
High school	7	.38	(–.12, .89)	55.4*	
Ability level					
Mixed	16	.23	(–.01, .46)	87.2*	28.7*
High	2	1.06	(–.24, 2.37)	18.5*	
Treatment length					
0–3 weeks	5	.21	(–.26, .67)	18.7*	14.2*
4–8 weeks	4	.40	(–.43, 1.22)	79.9*	
9 or more weeks	9	.32	(.06, .58)	21.8*	
Calculator use					
Functional	5	.36	(–.18, .90)	64.6*	27.9*
Pedagogical	13	.32	(.07, .58)	42.0*	
Calculator type					
Basic/scientific	10	.17	(–.10, .44)	39.9*	47.8*
Graphing	8	.49	(.11, .87)	46.7*	

Note. k = number of studies; g = weighted mean effect size; CI = 95% confidence interval for g; Q_W = homogeneity statistic; Q_B = difference between contrasted categories
* $p < .01$

Increasing weighted mean effect sizes according to increasing division (g = .15, g = .28, g = .38, respectively) were the result of the analysis of educational division ($Q_B = 10.7, p < .01$). However, none of the values significantly favored the students using calculators during instruction. Based on the analysis of ability level, ($Q_B = 28.7, p < .01$), the weighted mean effect size for studies featuring high ability students (g = 1.06) was large, but it was based on data from only two studies. The effect size value for mixed ability classes (g = .23) was small and not statistically significant.

The 9 or more weeks category produced a small to moderate weighted mean effect size (g = .32) during the analysis of treatment length (Q_B = 14.2, $p < .01$). This result significantly favored the students who had access to calculators during instruction. The effect size values for the 0–3 weeks category and 4–8 weeks category (g = .21 and g = .40, respectively) were relatively similar in size, but neither value was statistically significant.

The weighted mean effect sizes for the functional (g = .36) and pedagogical (g = .32) categories were close in size after the analysis of calculator use (Q_B = 27.9, $p < .01$). The pedagogical result was statistically significant in favor of students who had access to calculators during instruction. Lastly, significant differences in the magnitudes of effect sizes were found with respect to calculator type (Q_B = 47.8, $p < .01$). The studies that featured the graphing calculator generated a moderate weighted mean effect size (g = .49) that was statistically significant for students who had access to calculators. The effect size value for studies using basic or scientific calculators was small (g = .17) and not statistically significant.

Summary of Major Findings

When calculators were included in instruction but not testing, the operational skills and the ability to select the appropriate problem-solving strategies improved for the participating students. Under these conditions, there were no changes in students’ computational skills and skills used to understand mathematical concepts. When calculators were part of *both* testing and instruction, the operational skills, computational skills, skills necessary to understand mathematical concepts, and problem-solving skills improved for participating students. Under these conditions, there were no changes in students’ ability to select the appropriate problem-solving strategies. Students who used calculators while learning mathematics reported more positive attitudes toward mathematics than their noncalculator counterparts on surveys taken at the end of the calculator treatment.

DISCUSSION

The purpose of this meta-analysis was to determine the effects of calculators on students’ acquisition of operational and problem-solving skills as well as student attitudes toward mathematics. The studies on which these results were based were conducted primarily in classrooms in which students were engaged in a traditional mathematics curriculum. The reader should keep in mind that in most cases, the participating classrooms were not using curriculum materials specifically designed for calculator use, but at the same time, it should be noted that in two thirds of the studies the calculator had an active role in the teaching and learning process.

Overview of Findings

When calculators were available during instruction but not during testing, students in grades K–12 maintained the paper-and-pencil skills and the skills necessary to understand mathematical concepts. The operational skills of these students improved as a result of calculator use during instruction. Students received the most benefit when calculators had a pedagogical role in the classroom and were not just available for drill and practice or checking work. The results for operational skills favored mixed ability classes, with high ability students neither helped nor hindered by calculator use during instruction. The meta-analysis reported here does not include results for low ability students. In order to have a positive influence on students' operational skills, the findings suggest that calculator use during instruction should be long term (i.e., 9 or more weeks). With respect to problem solving, the skills of precollege students were not hindered by the inclusion of calculators in mathematics instruction. Based on a limited number of studies, the skills necessary to select the appropriate problem-solving strategies may improve as a result of calculator use.

When calculators were included in testing and instruction, students in grades K–12 experienced improvement in operational skills as well as in paper-and-pencil skills and the skills necessary for understanding mathematical concepts. With regard to operational skills and conceptual skills, the results of calculator use were most significant for classes in which the calculator's role was pedagogical. The calculator benefited students in mixed ability classes and classes consisting of high ability students. The meta-analysis does not report results sufficient for generalizations to be made for classes of low ability students. When the calculator was included in testing and instruction of conceptual skills, students benefit from short term (0–3 weeks) use of calculators. Benefits to operational skills can be seen with short term or long term (9 or more weeks) calculator use.

Under the same testing and instruction circumstances, improvement in problem-solving skills for students in mixed ability classes appeared in the results. This meta-analysis does not provide sufficient data for generalizations for classes consisting of low or high ability students. Students' abilities to select the appropriate problem-solving strategies were not hindered by the calculator's role in testing and instruction. The increase in problem-solving skills may be most pronounced under two conditions: (1) when special curriculum materials have been designed to integrate the calculator in the mathematics classroom and (2) when the technological tool in use was the graphing calculator. These results should be interpreted with caution because the data are based on a small number of studies.

Allowing students to use calculators in mathematics may result in better attitudes toward mathematics. In this study, attitudes showed the most improvement after 9 or more weeks of calculator use. Students' self-concept in mathematics and attitude toward the use of calculators in mathematics were not hindered by calculator use.

In this meta-analysis across all constructs, the results for studies lasting 4–8 weeks either favored students who did not have access to calculators during instruction or did not show significant differences between the two groups. For many constructs, the results based on studies lasting less than 4 weeks or more than 8 weeks were favorable for calculator use. This discrepancy may be related to students' abilities to retain what they learn. In short-term studies, retention was not assessed, but in long-term studies, retention was somewhat significant especially with concepts learned early in the treatment phase.

Based on the nature of the data gathered from the 54 studies, the effect of calculator use in individual grades could not be determined. Hembree and Dessart (1986, 1992) reported in their meta-analysis that when calculators were not allowed during testing, the use of calculators in instruction had a negative effect on the computational skills of students in fourth grade. Unfortunately, this particular result could not be supported or disproved by the current meta-analysis. Based on studies conducted within the elementary division, the development of computational skills was not hindered by calculator use during instruction for both with and without calculator use in testing.

When calculators were not allowed during testing, results were not significantly different for one type of calculator as compared to the others. When calculators were an integral part of the testing process, the results based on graphing calculator use were significantly better than the results of basic or scientific calculators in two areas: conceptual skills and problem-solving skills. Operational skills benefited from all three types of calculators. Lastly, graphing calculators had a more significant influence on students' attitudes when compared with other types of calculators.

Recommendations for Classroom Usage

The results from this meta-analysis support the use of calculators in all precollege mathematics classrooms. When considering the grade distribution of the studies based on the educational divisions (elementary, middle, high school), length of calculator availability during instruction should increase with each increasing grade level. Because limited research has been conducted featuring the early grades, calculator use should be restricted to experimentation and concept development activities. Calculators should be carefully integrated into K–2 classrooms to strengthen the operational goals of these grades, as well as foster students' problem-solving abilities.

Calculators should especially be emphasized during the instruction of problem-solving skills in middle and high school (i.e., Grade 6 through Grade 12) mathematics courses. This emphasis may result in increased success in problem solving as well as more positive attitudes toward mathematics. Teachers should design lessons that integrate calculator-based explorations of mathematical problems and mathematical concepts with regular instruction, especially in these grades. Calculators should be available during evaluations of middle and high school students' problem-solving skills and their understanding of mathematical concepts. This recommendation is based on the results reported in this meta-analysis, and the inconsistencies noted by other reviewers (Gilchrist, 1993; Penglase & Arnold, 1996;

Roberts, 1980) that occur when tests are given without calculators after instruction has taken place with calculators.

Recommendations for Future Research

Considering the search conducted to gather relevant studies and recognizing the fact that this paper does not fully address many questions that have been raised by mathematics educators, I propose several areas in which further calculator-based research is needed. Only a few studies involved the calculator's role in the retention and transfer of operational skills and students' abilities to select the appropriate problem-solving skills. Researchers need to consider students' abilities to select appropriate problem-solving strategies in light of available technology and to retain their operational and problem-solving skills after instruction with calculators. Also, further research is needed regarding the transfer of skills to other mathematical subjects and to areas outside of mathematics.

Based on the definition used to identify a mathematical skill as a problem-solving skill in preparing for this meta-analysis, little information was available on the relationship between the graphing calculator and student achievement in problem-solving skills. The studies featuring the graphing calculator primarily focused on the acquisition of operational skills; consequently, the problem-solving results were primarily based on basic and scientific calculators. Therefore, future research should include studies of graphing calculator use in the development of problem-solving skills.

In spite of the fact that the NCTM (1989, 2000) has been advocating changes to the mathematics curriculum with computer and calculator technology as an integral component, the search for studies for this meta-analysis yielded only six studies in which special curriculum materials were designed for calculator use. Because this number reflects only 11% of the studies analyzed, this is an area in which more research needs to be conducted.

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APPENDIX

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