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The Effects of Hand-Held CAS on Student Achievement in a First Year College Core Calculus Sequence

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This study investigated the impact of the TI-89 hand-held Computer Algebra System (CAS) on student achievement in a first year college core calculus course. The researchers analyzed data from an experimental study conducted at the United States Military Academy at West Point in 1998-2000. Scores of common final exam questions were compared between students who used the hand-held CAS in 1999-2000 and students who used a different calculator in 1998-1999. The results of the achievement study indicated that the TI-89 hand-held CAS experimental group attained a higher mean score than the control group on thirteen of twenty items. Among the twenty items, the only significant differences in mean scores ($p < 0.05$) were found in eight of the items favouring the experimental group.

1. INTRODUCTION

A nationwide effort to revitalize the teaching and learning of calculus commenced over a decade ago. Studies investigating the impact of both calculator and computer integration into mathematics courses cite student improvement in conceptual understanding and maintenance of procedural skills (Connors, 1995; Crocker, 1993; Cunningham, 1992; Estes, 1990; Heid, 1985, 1988; Hurley, Koehn, & Ganter, 1999; Judson, 1990; Keller & Russell, 1997; Siler, 1990; Tufte, 1990), and improvement in problem solving (Bookman & Friedman, 1994). Other investigations reported an increase in the percentage of students who enjoyed the computer calculus course (Boyce & Ecker, 1995) or had a more positive attitude toward mathematics and computers (Park, 1993; Siler, 1990). Prior studies conducted from the late 1960's to 1987 on using the computer to enhance calculus instruction showed only a small, positive, but not significant, effect on student achievement (Teles, 1992). However, when conceptual understanding and manipulative skills were tested separately, use of the computer resulted in favourable significant differences in conceptual understanding.

Hurley, Koehn, & Ganter, (1999) cite a National Science Foundation study to evaluate the effect of technology use in calculus:

> ...approximately 50% of the institutions conducting studies on the impact of technology reported increases in conceptual understanding, greater facility with visualization and graphical representations, and an ability to solve a wider

> variety of problems, without any loss of computational skills. Another 40% reported that students in classes with technology had done at least as well as those in traditional classes. (p. 809).

For example, Hurley, Koehn, & Ganter (1999) discuss experiments at the University of Connecticut at Storrs and at Dartmouth. For every semester from Fall 1989 through Spring 1994 at the University of Connecticut, students in the computer-integrated course using *True-BASIC* performed significantly better than students in the traditional calculus course on the common final exam. The study suggested that the students in the experimental sections attained better conceptual understanding without a difference in hand-computational skills. On the other hand, the experiment at Dartmouth using *True-BASIC* in 1988 found no differences in performance on the same traditional final examination between students in the first term introductory calculus course and students taking the same course the prior year when the degree of computer use was substantially lower.

A comparative study (Park, 1993) of the traditional calculus course and the Calculus & *Mathematica* (C&M) course, using quantitative and qualitative analysis, indicated that the experimental group, without seriously losing computational proficiency, was much better at conceptual understanding than was the traditional group. The attitude survey results connoted that the C&M group's disposition toward mathematics and computers was far more positive than that of the traditional group. Crocker (1993) also reported improvement in the understanding of the concept of derivative in a calculus class immersed in *Mathematica*. In addition, Connors (1995) reported significant differences favoring student achievement in a computer-integrated course and also suggested that female students in the computer-integrated calculus course benefited more than any other subgroup.

An experiment using *True BASIC* Calculus and *Calculus Toolkit* (Siler, 1990) disclosed that student response to the labs was generally positive and the students' grasp of fundamental concepts was generally stronger than that of other similar groups with which the author worked. Judson (1990) reported that an experiment using the computer algebra system, *Maple*, in elementary business calculus convinced her that computer algebra systems could be used successfully in college mathematics instruction. Tufte (1990) noted that the experimental subjects required to write computer programs were better able than the control subjects to recognize various forms of the definitions of the derivative and integral, and to relate algebraic representations of functions to the graphical representations. Heid (1985, 1988) also concluded, from an experimental study in resequencing skills and concepts in applied calculus using computers, that students from the experimental classes spoke about the concepts of calculus in more detail, with greater clarity, and with more flexibility than did students of the comparison group.

Studies using hand-held technology also support these findings. An investigation of the effectiveness of the use of computers and hand-held graphing calculators in applied calculus (Estes, 1990) revealed that the calculator and computer technologies positively impacted conceptual achievement. Students believed that the calculator and computer technologies were helpful in their learning if the student understood how to use the technology. Keller & Russell (1997) reported that the students using the TI-92 hand-held graphing calculator with CAS were more successful at symbolically solving problems than comparison students.

Other studies (Melin-Conejeros, 1993; Hamm, 1990; Thongyoo, 1989) countering these claims cite design of the courses, equipment and software, location of facilities/equipment and nature of homework/assignments as factors influencing their results. Melin-Conejeros (1993) investigated the effects of doing calculus homework assignments with *DERIVE* on students' achievement and attitude towards mathematics. The 12 students in the experimental class were assigned homework that was to be done in the computer laboratory with *DERIVE*. *DERIVE* was not used for class instruction. The 16 control group students completed the same type of homework without the computer. He reported that there were no differences between treatment groups on overall achievement or attitudes. However, interviews revealed that students who had used *DERIVE* for their homework had a better understanding of selected concepts: increasing and decreasing functions, asymptotes, concavity of graphs of function, limits of functions, and continuity. Thongyoo (1989) reported no significant difference between the achievement of students taught by using *The Calculus Toolkit* and those taught by the traditional method. He pointed to some factors that might have affected these findings, such as: the nature of the assignments, class time, location of the microcomputers, and the software. Hamm (1990) also recorded that the use of the microcomputer in introductory calculus did not significantly influence either student achievement in calculus or student attitude toward mathematics.

In a study on the effects on achievement of using *True BASIC* software capable of symbolic manipulation to reduce hand-generated symbolic manipulation in freshman calculus, Cunningham (1992) concluded "the use of *True BASIC* improved achievement and did not cause damaging effects when access was denied (p. 2448-A)." He did note, however, that this success required use of the software in class by the instructor and extensive out of class use by the students.

2. THE STUDY

This study was conducted during the 1999-2000 academic year at the United States Military Academy at West Point (USMA). The purpose of this study was to investigate the impact of the integration of the TI-89 hand-held computer algebra system on students' achievement and attitudes in the first year core calculus sequence. Results and discussion of the attitude portion of the study are reported in a separate publication (Snook & Connors, submitted for publication). In the achievement study, the researchers were interested in studying the effectiveness of the hand-held CAS in enhancing the teaching and learning of mathematics. The goal of this study was to analyze the achievement of students enrolled in Fall 1999 and Spring 2000 with those enrolled in the same courses Fall 1998 and Spring 1999. The primary data sources were common final exam items.

The integration of the TI-89 calculator into the USMA curriculum is more accurately described as the integration of a hand-held computer algebra system. While the studies above compared technology users to non-users, this study looks at changes in technology users after integrating a new tool with additional capabilities. In most experiments cited above students did not use the computer-algebra system on exams. Students at USMA were permitted to use the TI-89 on the final exam.

3. METHOD

Setting and Participants

All students at USMA take four semesters of core mathematics. The mathematics curriculum is very applied and focuses on modelling and problem solving. The educational philosophy within the Department of Mathematical Sciences embraces active learning and student-centered instruction. Instructors expect students to read the current lesson and work on assigned problems prior to class time. In class, students engage in discussing concepts and working problems at the blackboards or at their seats. Student exploration, experimentation, cooperative and collaborative activities, and group discussion are the norm. Small class size – 16 to 18 students – is conducive to significant interaction between teachers and students.

Technology, in the form of graphing calculators and computer algebra systems, has been integrated into the classes, courses and curriculum at the study site for over a decade. Scientific computing is an integral part of the curriculum. Prior to the integration of the TI-89 hand-held CAS in the fall of 1999, all students were using the HP48G graphing calculator. Students may use the calculator at all times in class and on most exams, including the final exam. Additionally, students use the computer software *MathCAD* outside of class as they work on homework and projects. Computers were not used on the final exams in any year.

USMA requires all students to complete core courses in Discrete Dynamical Systems and Introduction to Calculus (4.0 credits) and Calculus and Differential Equations (4.5 credits). The Academy's Registrar Office randomly assigns students to course sections. In these courses all sections follow a common syllabus and course guide. During the differential and integral calculus portions of these courses, the text, *Calculus Concepts and Contexts* by Stewart is used. Three course-wide exams, two course-wide projects and a common final exam constitute about 75% of the course grade. Course instructors group grade all exams. Neither the students nor the instructors were aware that the final exam results would be analyzed for this study.

Researchers randomly selected experimental and control groups from among students enrolled in these two courses during the fall and spring semesters of the 1998-1999 and 1999-2000 academic years. Selection was done as follows:

Experimental Groups.

A sample of 100 final exams was randomly selected from both the Fall 1999 Discrete Dynamical Systems and Introduction to Calculus course population (n=898) and the Spring 2000 Calculus and Differential Equations course population (n=857). The students used the TI-89 hand-held CAS during these semesters and on these final exams.

Control Groups.

A sample of 100 final exams was randomly selected from both the Fall 1998 Discrete Dynamical Systems and Introduction to Calculus course population (n=988) and the Spring 1999 Calculus and Differential Equations course population (n=956). The students used the HP48G calculators, and/or any calculator without a "qwerty" keyboard, during these semesters and on these final exams. (The TI-89 calculators were not yet on the market. The use of the TI-92 was not permitted.)

Data

Common final exam questions provided information about students' achievement performance on course skills and concepts. Comparative exam data were obtained for each student in the experimental and control groups. The final exams varied only slightly from year to year. Course exams had been previously graded by groups of instructors according to a common grading scale/rubric. A study database was developed with scores for each chosen question and sub-question. Questions were chosen for use in the study if they met two criteria. First, questions were limited to those addressing topics normally covered in a first year calculus sequence (differential and integral calculus). Second, each question chosen had to be worded and presented exactly the same, or with minimal variation, on comparison year exams.

Preliminary Analysis

Before beginning analyses of the Final Exam results, means of the SAT/ACT-Math score, final exam score and final course grade for each of the four sample groups were compared to the respective means of their associated overall population, as well as to each other, by a z-test. There were no significant differences found between the control and experimental sample groups and the populations they represented on these measures. There were also no significant differences in the means of these measures between the populations from which the control and experimental groups were drawn. Furthermore, a comparison of the control and experimental groups within each course yielded no significant difference in the means of these measures. Tables 1 and 2 depict these mean data.

Discrete Dynamical Systems & Introduction to Calculus Measure	Control – Fall 1998 Population N=988*	 Sample N=100*	Experimental – Fall 1999 Population N=898*	 Sample N=100*
Mean SAT*	631	633	629	625
Mean ACT*	28	28	27	27
Mean Final Exam Grade	85.21	83.71	80.99	82.98
Mean Course Grade	85.96	81.81	81.4	82.47
* Note: Not all in the population or sample group took the SAT or ACT. Approximately 90% take the SAT and 60% take the ACT.				

Table 1 –Measure Means for Control and Experimental Groups (Fall Terms)

Calculus I & Differential Equations Measure	Control – Spring 1999 Population N=956*	 Sample N=100*	Experimental – Spring 2000 Population N=857*	 Sample N=100*
Mean SAT*	631	636	630	636
Mean ACT*	28	27	27	28
Mean Final Exam Grade	74	71.76	76.2	75.38
Mean Course Grade	78.89	78.87	79.6	80.61
* Note: Not all in the population or sample group took the SAT or ACT. Approximately 90% take the SAT and 60% take the ACT.				

Table 2 – Measure Means for Control and Experimental Groups (Spring Terms)

Analysis

Within each of the courses (Discrete Dynamical Systems and Introduction to Calculus, Calculus and Differential Equations), the experimental and control groups were compared for statistically significant differences in question/sub-question means through use of a z-test. Using the question selection criteria (differential calculus course topic and minimum variation over the two exam years), a total of twelve exam questions were chosen for analysis. These exam questions were categorized as procedural, conceptual or an application (requiring a combination of conceptual and procedural knowledge). Procedural problems required knowledge and understanding of procedures and algorithms in their solutions. Conceptual problems were more conceptual than procedural, requiring knowledge and understanding of concepts to determine a solution method or response. The applications required that a student first interpret the problem and recognize a particular concept, and then apply a procedure or algorithm in their solution process. The goal of this categorization was to attempt to relate any identified differences in achievement performance on exam items to types or presentation of problems. Analyzed questions included three procedural questions, five conceptual questions and four application questions.

Question Type	Description	Mean % Control	Mean % Experi-mental	(*p*-value)	Performance Group Favored
Procedural	1a. Limit of a function (rational)	94.08	96.80	.118	
	1b. Limit of a function (rational)	81.20	94.30	.0001	Experimental
	2a. Differentiation (Product Rule)	91.60	94.25	.155	
	2b. Differentiation (Power/Chain)	94.50	93.40	.322	
	2c. Differentiation (Quotient)	80.65	90.65	.0001	Experimental
	3. Graphing Function	87.00	86.67	.455	
Conceptual	4. Graph of f'(x) from graph of f(x)	84.77	85.00	.475	
	5a. Average Rate of Change	83.00	82.56	.449	
	5b. Instantaneous Rate of Change	81.80	82.68	.409	
	6a. Extreme Values	71.87	69.82	.320	
	6b. Points of Inflection	74.67	70.80	.251	
	7. Graphical Relation f(x) & f'(x)	92.67	90.00	.210	
	8a. Integration – Extreme Values	51.48	70.05	.0002	Experimental
	8b. Integration – Absolute Extrema	72.00	67.5	.241	
Application	9a. Position to Velocity	87.30	95.25	.004	Experimental
	9b. Position to Acceleration	85.40	94.00	.005	Experimental
	9c. Particle at Rest	77.45	82.50	.115	
	10. Optimization (Soda Can)	65.625	72.3	.044	Experimental
	11. Related Rates (Conical Pile)	67.17	75.48	.018	Experimental
	12. Diff Eqn / Model & Solve (Radioactive Decay)	72.25	90.69	.0001	Experimental

Table 3 – Comparison of Exam Items for Control and Experimental Groups

4. RESULTS

Analyses of the twelve chosen exam questions revealed significant differences in performance between the comparison groups. The exam questions with more than one part/requirement were analyzed by sub-question. In total, twenty items were analyzed. Table 3 summarizes the statistical analysis of comparing the performances of the control and experimental groups. A discussion of the results of the three various types of questions and the specific questions of each type follows this summary table.

Of the twenty items analyzed, the TI-89 experimental group attained a higher mean score on thirteen items. Of these items, eight were significant at the $p < 0.05$ level. In none of the seven items where the control group outperformed the TI-89 experimental group were the means significantly different ($p > .210$ in all cases). The most significant differences occurred in items classified as applications – five of six items significantly favored the experimental group. In each of these items students had to determine what concept to apply, develop a model applying that concept and then actually solve their model. Two of the six procedural items showed significant differences favouring the TI-89 group, while one of eight conceptual items significantly favoured the TI-89 group.

Procedural Items

Test items classified as procedural are presented in Table 4. These items tested procedures of taking limits, evaluating derivatives and sketching a graph from a function. Students in the control group had access to a graphing calculator that performed symbolic differentiation, but did not evaluate limits. The TI-89 hand-held CAS does both.

Most students in both groups showed hand calculation work on both the limit and differentiation problems. Significant differences were only seen on the most complex of the two types of problems – the infinite limit that did not reduce by factoring and the differentiation involving both the quotient rule and a trigonometric function. The "graphing a function" item showed no difference between groups, but it is interesting to note that only 87% of students were able to graph this quadratic function when both groups had access to a graphing calculator.

Question / Item	Mean % Control	Mean % Experimental
1. Find the following limits:		
a. $\lim_{x\to -1} \frac{x^2 - x - 2}{x + 1}$	94.08	96.80
b. $\lim_{x\to\infty} \frac{x^2 - x - 2}{3x^2 + 1}$	81.20	94.30* ($p < 0.0001$)
2. Find the derivatives of the following functions:		
a. $r(q) = (e^q + q^2)(\sin(q))$	91.60	94.25
b. $p(s) = (s^4 + 7s)^3$	94.50	93.40
c. $c(t) = \frac{\cos t}{4t + t^5}$	80.65	90.65* ($p < 0.0001$)
3. Given $f(t) = 3t^2+1$, where t is measured in hours and $t = 0$ occurs at 4:00 a.m., graph this function on the grid below over the interval [-4, 4] which corresponds to the time period from midnight to 8 a.m. (square grid provided for student's graph)	87.00	86.67

Table 4 – Comparison of Procedural Items

Conceptual Items

Test items classified as conceptual are presented in Table 5. These items tested concepts based in interpretations of the derivative as slope and as rate of change. Several items included graphical representations of the concepts of differentiation and integration. Both groups of students had access to graphing calculators.

The only item showing a difference between groups involved a graphical interpretation of integration. With the TI-89, students in the experimental group could graph the function defined by an integral on their calculator and then analyze the resulting graph. Students in both groups struggled equally with the concept of average rate of change, as well as finding and classifying extrema and points of inflection.

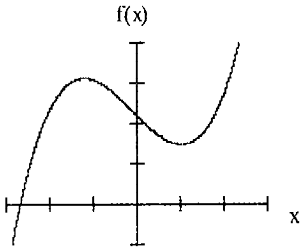
Question / Item	**Mean % Control**	**Mean % Experimental**
4. The graph of a function, $f(x)$, is shown below. Sketch the graph of the derivative of the function, $f'(x)$, on the axis provided. 	84.77	85.00
5. a. Given the function for temperature at time t: $f(t)=3t^2+1$, what is the average rate of change of temperature between 5 a.m. and 8 a.m. (t=0 occurs at 4 a.m.)?	83.00	82.56
b. What is the instantaneous rate of change of temperature at 6 a.m.?	81.80	82.68
6. Given the function $y(x) = 12x^2-15x$ on the interval [0, 2.5] a. List and classify all extreme values of $y(x)$ over the given interval.	71.87	69.82
b. Determine whether or not there are any point(s) of inflection for the function $y(x)$. Justify your answer.	74.67	70.80

Table 5a Comparison of Conceptual Items

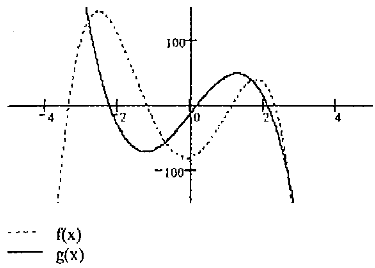
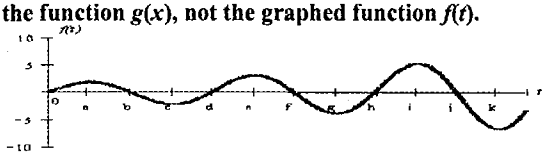
Question / Item	Mean % Control	Mean % Experimental
7. Two functions f and g are shown below. Choose which of the following statements best describes the situation pictured. Provide an explanation of your choice. (a) f is the derivative of g. (b) g is the derivative of f. (c) Neither function is the derivative of the other. (d) I cannot tell or not enough information is given. I chose ____ (letter above) because: ______________________________ ______________________________ ______________________________ 	92.67	90.00
8. Let $g(x) = \int_0^x f(t)\,dt$, where $f(t)$ is the function whose graph is shown. **NOTE: The questions below refer to the function $g(x)$, not the graphed function $f(t)$.**  a. At what values of x do the local maximum and local minimum values of $g(x)$ occur? b. Where does $g(x)$ attain its maximum value on the interval [0, k]	 51.48 72.00	 70.05* ($p < 0.0002$) 67.50

Table 5b – Comparison of Conceptual Items

Application Items

Test items classified as applications are presented in Table 6. These items tested students' ability to interpret the problem, and then determine what calculus concept to apply to model and solve the problem.

The items classified as applications showed the most significant differences between control and experimental groups. The experimental group outperformed the control group on applications of motion (position-velocity-acceleration), optimization, related rates and radioactive decay. Students in the experimental group understood and applied basic calculus concepts to outperform the control group in all six items and significantly do so in five of those six.

Question / Item	Mean % Control	Mean % Experimental
9. A particle travels along a path according to a position function of $s(t)=2t^3-9t+12$, where s is measured in meters and t is measured in seconds.		
a. Find the particle's velocity after 2 seconds.	87.30	95.25* ($p < 0.004$)
b. Find the particle's acceleration after 3 seconds.	85.40	94.00* ($p < 0.005$)
c. Find the time(s) when the particle is at rest.	77.45	82.50
10. A manufacturer of a soft drink wants to construct a right circular cylinder can to hold 375 ml of the soft drink ($V=\pi\ r^2\ h$). Determine the height, h, and radius, r, in centimeters that minimizes the total surface area ($SA = 2\ \pi\ r^2 + 2\ \pi\ r\ h$) of the can (include a top and a bottom). Also, show that the dimensions you find actually minimizes the surface area (Note: 1 ml = 1 cm^3).	65.625	72.3* ($p < 0.044$)
11. Sand is poured onto a conical pile ($V = \frac{1}{3}\pi r^2 h$) at a rate of 10 m^3 / min. If the width of the base of the pile is always one-third the height of the pile, find the rate at which the height of the pile is changing when the pile is 6 m high. Show all your work.	67.17	75.48* ($p < 0.018$)
12. A radioactive substance decays at a rate proportional to the amount of substance present. The initial amount of the substance is 100 grams. After 5 years, there are 85 grams left. Model this situation with a differential equation. Solve your model to find a function describing the amount of substance present at any time. Be sure to define all variables used and solve for all unknown constants.	72.25	90.69* ($p < 0.0001$)

Table 6 – Comparison of Application Items

5. DISCUSSION

The results of this study support the assertion that appropriate use of a hand-held computer algebra system can enhance the teaching and learning of calculus to achieve improved procedural, conceptual and application performance. Core undergraduate mathematics courses are content laden. Although the calculus reform movement called for "lean and lively" courses, changes occurred more often in pedagogy than in content or material (Douglas, 1995; Tucker & Leitzel, 1995). This study has applications and implications that touch both pedagogy and content.

Many reform projects included a technology component. Technology is touted to offer efficiencies that allow students and teachers time for deeper exploration of the concepts. One example of a realized benefit is in function graphing. Students can quickly produce a graph on their hand-held calculator and then spend time analyzing the graph's properties. By graphing a function and its derivative on the same axes students gain deeper insights into how these two graphical representations, and ultimately these two functions, are related. With the latest calculators students can easily determine and evaluate derivatives, as well as indefinite and definite integrals. These advantages appear to have offered some significant benefits to students at this study site. We especially note the significant differences found in the application problems. In these items students must have a grasp of both the concepts and the procedures needed to interpret and solve the problem. In the four typical applications of differential calculus included in this study (motion, optimization, related rates, exponential decay), the experimental group significantly outperformed the control group. With the same syllabus, same textbook and similar classroom environments, the only differing factor was the integration of the TI-89 hand-held computer algebra system.

As we continue to integrate technology into the mathematics classroom, we also need to continue to question its impact and make decisions as to when and how to integrate technology appropriately. Does integration of this technology mean that we no longer need to teach differentiation and integration rules and techniques? How will students develop an appreciation for when technology is or is not efficient or appropriate? Will the time saved by technology offer a chance to look at key topics in a more conceptual manner? How will use of this technology affect students' procedural and conceptual knowledge? How does the integration of technology impact the way we assess students?

Studies like the one presented here will inform instruction and assessment decisions made by teachers. This study will facilitate continued discussion and research into these important questions. Additional research is needed to study the long-term effects of early integration of technology on mathematics majors, as well as mathematics intensive majors. Follow on studies are needed to determine if technology is enhancing the mathematical skills and concepts of these mathematics users.

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