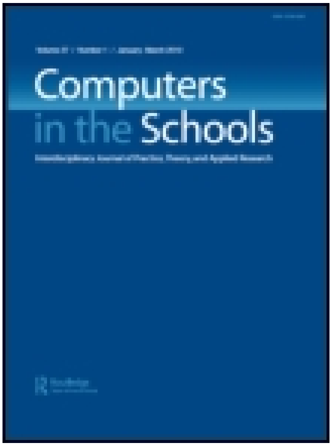

Computers in the Schools: Interdisciplinary Journal of Practice, Theory, and Applied Research

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/wcis20

A Study of the Effectiveness of Computer-Based Simulations in Teaching Computer Architecture

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Published online: 13 Oct 2010.

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INTRODUCTION

A computer-based simulator is a program that models a realistic situation because it requires active participation by the user in initiating and performing inquiries, decisions, and actions. In addition to providing an opportunity to acquire skills, attain new concepts, and engage in problem solving, a simulation can provide a student with immediate feedback and rapid repeatability without concern for the time and expense involved in using real materials (Gorrell, Cuevas, & Downing, 1988; Lunetta & Hofstein, 1981; McGuire, 1976; Spain, 1984; Strickland & Poe, 1989). Most educational settings require simple forms of simulators. Details are changed or omitted to provide thought or engage the student in participation (Strickland & Poe).

Currently, the literature suggests that the use of simulators is advantageous for students; however, not all claims are accompanied by documented evidence (Gorrell et al., 1988). A variety of educational settings use

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[Haworth co-indexing entry note]: "A Study of the Effectiveness of Computer-Based Simulations in Teaching Computer Architecture." DeNardo, Anette M. and Anthony S. Pyzdrowski. Co-published simultaneously in *Computers in the Schools* (The Haworth Press, Inc.) Vol. 10, No. 1/2, 1994, pp. 125-140; and: *Multimedia and Megachange: New Roles for Educational Computing* (eds: W. Michael Reed, John K. Burton, and Min Liu) The Haworth Press, Inc., 1994, pp. 125-140. Multiple copies of this article/chapter may be purchased from The Haworth Document Delivery Center [1-800-3-HAWORTH; 9:00 a.m. - 5:00 p.m. (EST)].

computer-based simulations. The study of computer architecture is one such area. Because students cannot study the internal architecture of a computer system, computer programs to simulate the architecture are frequently used. Unfortunately, research on their effectiveness is almost nonexistent.

Three simulators were written for incorporation in a college-level course in computer architecture. This paper reports on a study of the simulators and their effect on student understanding of the architecture of computers.

REVIEW OF THE LITERATURE

The literature contains many discussions of computer-based simulations in relation to their instructional uses. Computer-based simulations are efficient, effective, highly motivational, serve the need for individualization, and enhance the transfer of learning by teaching complex tasks in a real world setting (Reigeluth & Schwartz, 1989) and should be used to augment classroom instruction (Bender, 1989; Spain, 1984; Strickland & Poe, 1989).

Although the use of computer-based simulations was well established by the mid-70s (Magin & Reizes, 1990), their use varies from one application to another. Some simulators establish a game-like environment (Taylor, 1987), while others are quite realistic (Lunetta & Hofstein, 1981). Simulators have been used in chemical (Smith, Jones, & Waugh, 1986) and biological experiments (Angier, 1983), in business (Remus, 1977), counseling (Halpain, Dixon, & Glover, 1987), computer programming (Hooper & Thomas, 1990), and environmental (Fortner, Schar, & Mayer, 1986) education.

Simulators provide the means to reproduce, or simulate, the essential parts of a real situation. While they should appear as lifelike as possible (Strickland & Poe, 1989), research has shown that high levels of physical and visual fidelity are not always required to obtain valid results (Alessi, 1987; Thompson, 1989).

There is some evidence that knowledge gained through the use of a simulation may generalize more freely to real-life situations (Alessi & Trollip, 1985). Students using computer simulations of chemistry (Cavin & Lagowski, 1978; Jackman, Moellenberg, & Brabson, 1990) and physics (Boblick, 1972) laboratory experiments performed as well as or better than students who did not use the simulations.

Other researchers have looked at the effects of computer-based simulations on student attitudes. Most students react favorably to computer-simulated situations (Gorrell et al., 1988; Louscher & Van Steenburg, 1977;

Taylor, 1987). Their use has promoted an increase in student interest (Taylor, 1987), increased student confidence (Gorrell et al., 1988), and caused students to attempt more problem solutions (Hooper & Thomas, 1990).

Computer simulations have helped students score significantly higher than their control group counterparts on knowledge tests (Fortner et al., 1986) and improve research design and applied skills (Collet & Shiffler, 1985). Structured simulation activities have proved to be as effective as conventional practices among nontraditional students (Rieber, Boyce, & Assad, 1990). And, in some cases, the students preferred the simulation format over the more traditional approach (Halpain et al., 1987).

In a review of recent research in the use of computers in instruction (Roblyer, Castine, & King, 1988), several important observations were made about simulations. They may assist in teaching problem-solving skills if used in ways that help students identify and use information to improve decision-making. Simulations used in science applications and at college and adult levels provide promising results. Yet, more research and field testing is needed to confirm or deny the variety of theories regarding their use (Reigeluth & Schwartz, 1989).

PURPOSE OF THE STUDY

This research was motivated by the need for supportive learning materials for students in a computer architecture course. With the support of interactive computer learning aids, the researchers expected to find that students had a better understanding of the course material. This research was conducted to study the effect of computer architecture simulations on student understanding of computer architecture.

RESEARCH QUESTIONS

Several research questions were addressed in this study:

1. To what extent does the use of computer-based simulators affect the students in low, medium, and high ability groups?
2. To what extent does the use of computer-based simulators affect student achievement in the computer architecture course?
3. How do students perceive the use of simulators in a computer architecture course?

DESIGN OF THE STUDY

Sample

Fourteen undergraduate students enrolled in a computer architecture course served as the subjects in this study. The students were computer science majors in a small state university in southwestern Pennsylvania.

Independent Variables

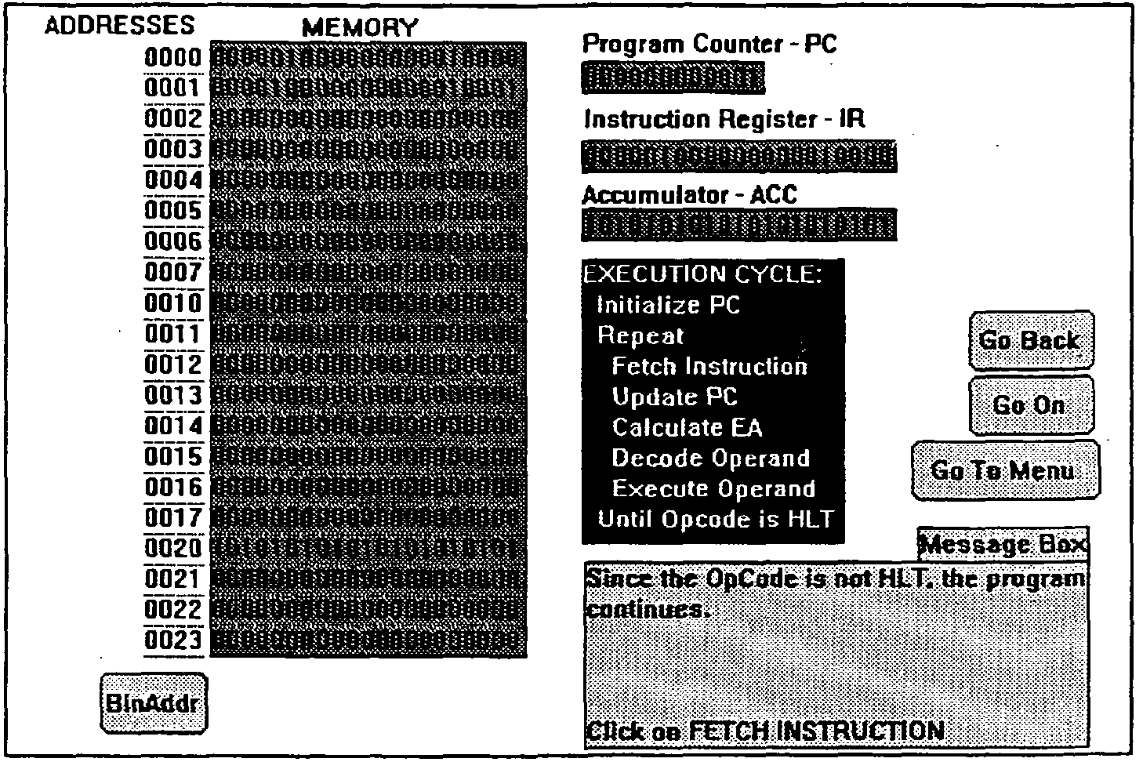
Blocking Variable. The students were separated into low, medium, and high ability-level groups based on their quality point average (QPA) for computer science courses. The average QPA score ($\bar{x} = 3.16$, $s = 0.71$) for all students in the study was calculated. Two students scored at least one standard deviation above the mean and were placed in the high-ability group ($QPA_H > 3.87$); four students scored at least one standard deviation below the mean and were placed in the low-ability group ($QPA_L < 2.45$); the remaining eight students were placed in the medium-ability group ($2.45 \leq QPA_M \leq 3.87$).

Treatment. Students from all ability groups began the semester with an introduction to the first simulator. It provided students with an introductory, self-paced tutorial of a hypothetical computer architecture, a content quiz, and an interactive machine-code program simulator that accepted student-written or "canned" programs. The first simulator contained three parts. The first part graphically presented basic information, introduced the architecture of the hypothetical machine, and presented the first 11 primary machine instructions.

A graphically animated quiz was used to evaluate the content learned in the first part of the first simulator. The quiz sequenced through three progressively difficult sections. An 80% competency rate was required for progress between sections; only then was the student exposed to an animated positive reinforcement.

In the third part of the first simulator, the operation of the hypothetical computer was demonstrated through a graphical presentation of its program execution and included the registers and memory (Figure 1). Several example programs were provided. As a program executed, the simulator changed the contents of the displayed components. An outline of the execution cycle, with the current step highlighted, appeared on the screen. By selecting a designated button, the student initiated the execution of an instruction. This provided a self-paced learning environment. Students could also enter their own programs in the simulator using binary or octal machine code.

FIGURE 1. Sample Screen from *Simulator One*



Near the midpoint of the course, students used a second simulator that demonstrated data flow at the machine level. The simulator supported class lectures on microsequences and contained a complete graphical rendering of the computer structure with buttons leading to further explanations of the components.

Following the graphical presentation of the computer, the simulator displayed a menu of 26 instructions. The student selected one instruction and a speed of presentation. The simulator displayed the microsequences for the selected instruction. The student selected one microsequence at a time and the simulator, using colors, traced the flow of data throughout the structure (Figure 2). These colored paths flowed throughout the structure at a rate proportional to the real operation time. The colored trace remained on the display for student scrutiny. The student could repeat this microsequence or select the next one. When all microsequences for the instruction were complete, the simulator returned to the menu.

The last simulator, written in C, was given to the students near the end of the semester. It accepted programs written by the students and demonstrated the execution sequence for the programs. Unlike the previous simulators, this package did not provide any educational instruction. The student entered a program from either the keyboard or a file. The output of the simulator could be sent to the display or another output file for a permanent record of the program execution. The output contained the contents of all registers for each instruction executed and the contents of memory upon program termination. There was no error detection or help within this simulator; its task was to test the effectiveness of the students' programming abilities with the new machine presented in the previous two learning simulators.

Dependent Measures

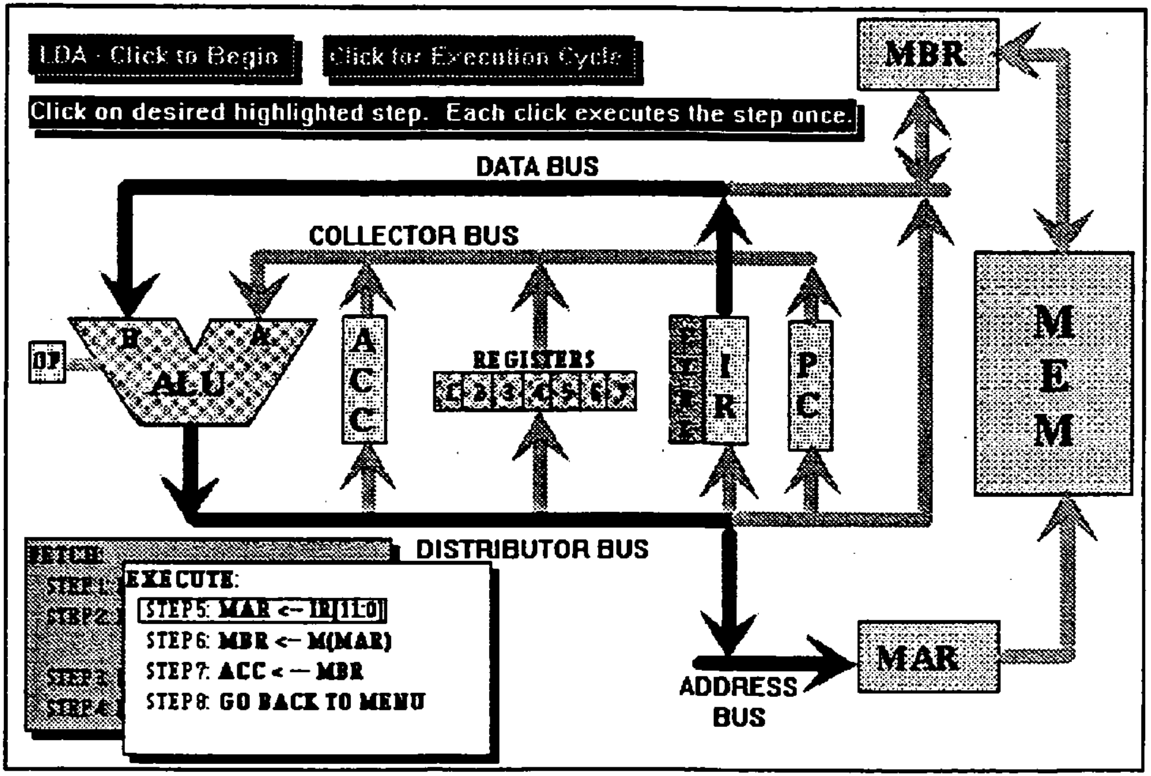
Pretest. At the beginning of the semester, the students were administered a pretest designed by the course instructor and validated by experts. It was used to evaluate student understanding of computer architecture at the beginning of the course.

Achievement Tests. The subjects were administered two instructor-prepared tests during the semester. A posttest was also used to measure student achievement.

Programming Assignments. The subjects wrote two programs using the third simulator. These programs were graded by the instructor of the class.

Surveys. The subjects completed a 13-item survey. It examined the time they spent on each of the three simulators, their perceptions of the effects the simulators had on their understanding of computer architecture con-

FIGURE 2. Sample Screen from *Simulator Two*



cepts and the instruction set of the computer, their perceptions of the effects of the simulators on their abilities to write programs and on the overall effectiveness of the simulators.

Procedures

The students were administered the pretest on the second class of the 30-class course. The first simulator was available for their use during the sixth class. Examination one was administered to the students during the 10th class. The second simulator was presented to the students during the 18th class. During the 24th class the final simulator was made available. The first two simulators were available on laboratory computers throughout the duration of the course. A copy of the final simulator was provided to the students for their individual use. No time restrictions were placed on usage, except that the students were expected to have used the simulators prior to the end of the course. Additionally, instructor assistance was available upon student request. Two programming exercises were assigned that made use of the third simulator. These assignments were made during the 25th and 27th classes. The second examination was administered during the 26th day of class. During the last day of class, the posttest was given.

Analysis of the Data

To what extent does the use of computer-based simulators affect the students in low, medium, and high ability groups? Five one-way ANOVAs were used to compare the mean scores on the two regular course examinations, the posttest, and the two programming assignments of the students in the three ability groups. In each ANOVA, ability grouping was the independent variable. If a statistically significant difference was detected, the Scheffé's test was used to determine the source of the difference.

To what extent does the use of computer-based simulators affect student achievement in the computer architecture course? T-tests were performed to determine whether or not significant gains were made between the pretest and first examination, the first and second examinations, the second examination and the posttest, and the pretest and posttest. These calculations were performed on all subjects and then on the subjects in each of the three ability groups.

How do students perceive the use of simulators in a computer architecture course? The results of a 13-item survey were examined. Trends in the subjects' responses were reported. The survey polled the subjects concerning the amount of time they spent on each of the three simulators, their understanding of computer architecture concepts and the instruction set of the hypothetical computer, their perceptions of the effects the simulators had on their ability to write programs, and the subjects' perceptions of the overall effectiveness of the simulators.

RESULTS

Achievement Measures

A one-way ANOVA was used to compare the means of the pretest, first examination, second examination, and posttest scores in the three ability groups (Table 1). There were nonsignificant differences for the pretest ($\bar{x}_L$ = 35.42; $\bar{x}_M$ = 28.02; $\bar{x}_H$ = 54.12). Significant differences were found for the

TABLE 1. Analysis of Variance of Pretest, Exam 1, Exam 2, and Posttest Scores for the Low, Medium, and High Ability Groups

SOURCE	df	SS	MS	F
Pretest:				
Between	2	1107.02	553.51	1.52
Within	11	4008.71	364.43	
Total	13	6222.75		
Exam 1:				
Between	2	1649.71	824.86	6.87*
Within	11	1320.66	120.06	
Total	13	2970.37		
Exam 2:				
Between	2	1037.49	518.75	4.95*
Within	11	1153.28	104.84	
Total	13	2190.77		
Posttest:				
Between	2	458.45	229.23	0.78
Within	11	3232.69	293.88	
Total	13	3691.14		

*$p < .05$

first regular course examination ($\bar{x}_L$ = 67.76; $\bar{x}_M$ = 89.48; $\bar{x}_H$ = 97.37). Using a Scheffé's test, significant differences were found between the low and medium group means and between the low and high group means. The low ability group performed significantly lower than the medium or high ability groups. Significant differences were found for the second regular course examination ($\bar{x}_L$ = 75.00; $\bar{x}_M$ = 91.05; $\bar{x}_H$ = 100.00). Using a Scheffé's test, significant differences were found between the low and high groups means, favoring the high ability group. There were nonsignificant differences found on the posttest ($\bar{x}_L$ = 76.67; $\bar{x}_M$ = 81.04; $\bar{x}_H$ = 95.00).

T-tests were performed to determine whether or not significant gains were made between the various examinations for all students and for students in each of the ability groups. Those results can be found in Table 2. Significant differences were found between the pretest and examination one, examination two and the posttest, and the pretest and posttest scores for all students. For the low ability group, there were significant gains pretest to examination one and pretest to posttest. For the medium ability group, there were significant gains pretest to examination one, examination two to posttest, and pretest to posttest. There were nonsignificant gains for the high ability group.

A one-way ANOVA was used to compare the means of the two programming assignments for the subjects in the three ability groups. There were nonsignificant differences on both programming assignments (F_{prog1} = 0.26; F_{prog2} = 1.22).

Percentage changes were calculated for the three ability groups from pretest to posttest. The medium ability group made the greatest gains of 289.22%, followed by the low ability group whose gains were 216.46%. The high ability group had the lowest gains of 175.37%.

Attitude Measures

Each of the 14 students in the study anonymously completed a survey. The survey asked for a self-reported indication of the time spent using the three simulators. The amount of time each student spent on the three simulators varied from less than one hour to more than three hours. One student used the first simulator for less than one hour; eleven students used it for one to three hours; two used it for more than three hours. All but one of the students used the second simulator for three or fewer hours. One student used the third simulator for less than one hour; seven students use it for one to three hours; six students use it for more than three hours. The third simulator was used for more hours than the first two simulators since the students were required to write two programs using that simulator.

The students who participated in the study indicated that the simulators

TABLE 2. Results of t-Tests on Various Examinations for All Subjects, Low Ability Group, Medium Ability Group, and High Ability Group

EXAMINATIONS	M_1	SD_1	M_2	SD_2	t
Pretest–Exam 1:					
All Subjects	33.87	19.84	84.40	15.12	8.25[1]
Low Ability	35.41	5.97	67.76	15.99	2.97[2]
Medium Ability	28.02	22.04	89.48	8.78	9.50[3]
High Ability	54.17	22.39	97.37	3.72	2.34
Exam 1–Exam 2:					
All Subjects	84.40	15.12	87.74	12.98	1.12
Low Ability	67.76	15.99	75.00	11.68	–0.95
Medium Ability	89.48	8.78	91.05	10.31	–0.41
High Ability	97.37	3.72	100.00	0.00	1.00
Exam 2–Posttest:					
All Subjects	87.74	12.98	81.79	16.85	–1.40[4]
Low Ability	75.00	11.68	76.67	19.00	–0.13
Medium Ability	91.05	10.31	81.04	17.43	2.36[5]
High Ability	100.00	0.00	95.00	4.71	1.50
Pretest–Posttest:					
All Subjects	33.87	19.84	81.79	16.85	8.28[1]
Low Ability	35.41	5.97	76.67	19.00	4.46
Medium Ability	28.02	22.04	81.04	17.43	6.07[3]
High Ability	54.17	22.39	95.00	4.71	3.27

$df_{ALL} = 13$ $df_L = 3$ $df_M = 7$ $df_H = 1$

1 $t_{crit} = 2.65$, $p = .01$ 2 $t_{crit} = 2.35$, $p = .05$ 3 $t_{crit} = 5.41$, $p = .0005$
4 $t_{crit} = 1.17$, $p = .05$ 5 $t_{crit} = 1.90$, $p = .05$

helped them to understand the concepts relating to the specific machine demonstrated in the simulators, helped them to understand the concepts relating to computer architecture, and made learning about computer architectures more concrete. Student responses were less strong when asked about using the simulators to write or understand programs written for the hypothetical machine. However, the majority of them agreed that the simulators had been helpful in these areas. They also agreed that the simulators helped them to understand the instruction set and microsequences of instructions for the hypothetical machine. The students agreed that the simulators helped them to better understand how other computer structures operate. And, although some students felt that they could have learned about the architecture of the hypothetical machine without the simulators, they recommend its use when the class is next taught.

DISCUSSION

Achievement Measures

The ANOVA performed on the pretest means for the three ability groups ($F = 1.52$) showed no significant differences between the means. This was expected since the content examined on the pretest consisted of information which the students should not have known. Therefore, the three groups were relatively equal in their knowledge of computer architecture concepts at the beginning of the semester-long study.

The significant differences between the pretest scores and the scores on the first examination were expected. Overall, there was a significant gain ($t = 8.25$) for all students in the study. Additionally, the increases for the low ($t = 2.97$) and medium ($t = 9.50$) groups were significant. These values were reflected in the percentage gains for these two groups (PG_L = 191.30%, PG_M = 319.34%). However, the gain for the high ability group was not significant (PG_H = 179.75%). A one-way ANOVA comparing the mean scores for the three ability groups on the first examination was significant ($F = 6.87$). The Scheffé test determined that the means for the high and medium ability groups were significantly higher than the mean of the low ability group.

It was expected that the high ability group would outscore the low and medium ability groups. What is important here is that the gains made by the low and medium groups were significant, while the gains made by the high ability group were not. Also, the percentage gain for the low ability group was greater than that for the high ability group. The reason the high ability group did not perform significantly better was that this group started out high; there was simply little room for improvement.

No significant differences were found in the score changes between the first and second examinations. However, the ANOVA performed on the means of the three ability groups on the second examination produced significant results ($F = 4.95$). The Scheffé test showed that the significant difference was between the low and high ability group means. On the first examination, both the medium and high ability groups significantly outscored the low ability group. On the second examination, only the high ability group significantly outscored the low ability group. If the percentage increases are examined (PG_L = 110.68%; PG_M = 101.75; PG_H = 102.70), it can be seen that each group increased their means; however, the greatest increase was within the low ability group. The reduced differences between the scores of the students in the different ability groups is attributed partially to the leveling off of the high ability group and improvement on the part of the medium and low ability groups.

A significant difference was found in the test scores between the second examination and the posttest. Overall, the scores dropped between the second examination and the posttest. When the ability groups were examined, the scores for the low ability group dropped while those for the medium and high ability groups rose. The gain for the medium ability group was statistically significant ($t = 2.36$). Perhaps the drop in overall scores can be explained by the nature of the examinations. The second examination tested the information covered after the first examination; the posttest was comprehensive.

A one-way ANOVA performed on the scores of the entire group on the posttest indicated no significant differences between the three group means ($F = 0.78$). This might show that the simulators had a leveling effect on the scores. However, the low and medium ability groups had significant gains in average scores ($t_L = 4.46$, $t_M = 6.07$) while the high ability group did not ($t_H = 3.27$). When these gains are expressed as percentage changes, the low and medium ability groups, as expected from the *t* scores, outperformed the high ability group (PG_L = 216.46%; PG_M = 9.22%; PG_H = 175.37%).

The same comprehensive examination was used as both the pretest and the posttest. The high ability group made nonsignificant gains in scores between all examinations. There was not much room for improvement in the scores of the subjects in the high ability group.

However, there were significant gains in examination scores for the low and medium ability groups. Subjects in the low ability group made significant gains pretest to examination one and pretest to posttest. Those in the medium ability group made significant gains pretest to examination one, examination two to posttest, and pretest to posttest. We hypothesize that these gains were due, at least in part, to the equalizing effect the simulators had on the subjects in the low and medium ability groups.

There were no significant differences between the set of scores of either programming assignment (program 1: $\bar{x}_L = 96.25$, $\bar{x}_M = 85.00$, $\bar{x}_H = 95.00$, $F = 0.26$; program 2: $\bar{x}_L = 83.75$, $\bar{x}_M = 61.25$, $\bar{x}_H = 95.00$, $F = 1.22$). These are not surprising results. The students were permitted to work on their programming assignments for a specified period of time; however, if the output was not correct, the students could alter the code. Perhaps use of the first two simulators influenced the subjects in the low and medium ability groups so that their resulting programs were not significantly different from those produced by the students in the high ability group.

Another reason for the lack of statistically significant differences in the group means on the pretest and posttest may be due to the small sample size ($n_L = 4$, $n_M = 8$, $n_H = 2$). With a larger sample size, the degrees of freedom would, of course, be greater and a smaller calculated F value would have been significant. If the means of the groups on the pretest ($\bar{x}_L = 35.42$; $\bar{x}_M = 28.02$; $\bar{x}_H = 54.12$) and posttest ($\bar{x}_L = 76.67$; $\bar{x}_M = 81.04$; $\bar{x}_H = 95.00$) are examined, it can be seen that they are different from each other; yet, the small sample size did not allow for significant differences.

Our results support the findings of other researchers who studied subjects in treatment and control groups. They often found that subjects who used simulations performed better than those who did not (Boblick, 1972; Cavin & Lagowski, 1978; Collet & Shiffler, 1985; Fortner et al., 1986; Jackman et al., 1990).

However, our findings contradict those of other researchers (Rieber et al., 1990; Schloss, Cartwright, Smith, & Polka, 1986-87). Schloss et al. (1986-87) studied low- and high-achieving college students who used simulation exercises; they found that the high-achievement group significantly outperformed the low-achievement group. Rieber et al. (1990) found that learning among non-traditional students was not influenced more by a simulation approach, although the structured simulation activity was as effective as the conventional method of presentation.

Attitude Measures

Based on the informal student surveys, the students favored the use of the simulators. These findings are in support of conclusions drawn by other researchers (Gorrell et al., 1988; Halpain et al., 1987; Hooper & Thomas, 1990; Taylor, 1987).

CONCLUSIONS

The use of the simulators benefitted the students, especially those in the low and medium ability groups, and may have equalized student achievement in the three ability groups. As reported in the surveys, the students have positive attitudes about the advantages of using the simulators.

Although these first findings are encouraging, more research needs to be done in this area. Larger sample groups should be studied. Student QPAs are based, in part, on the number of courses taken. Since this varies from student to student, the pretest should be used to separate the subjects into low, medium, and high ability groups. We feel this would be a better determiner of ability levels at the beginning of the course. Also, a more equal distribution of the subjects into the three groups is needed.

Individual interviews with the subjects should be conducted to gain the subjects' perspectives on the use of the simulators. An interview approach would permit researchers to gain a better perspective on student views of the architecture simulators. Additionally, other areas of the computer architecture, such as the ALU, can and should be simulated. This is an area of research that deserves further study.

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