Assessing Virtual Laboratories in a Digital-Filter Design Course: An Experimental Study

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***Abstract*—One hundred thirty-three undergraduate students in a digital filter design course participated in an experimental study. Two independent variables which occurred in a virtual laboratory environment were studied: 1) instructional treatments (online text-only materials, online texts with illustrations, and online texts with simulations); and 2) prior Internet experience (high and low). Three dependent variables were measured: 1) a knowledge achievement test; 2) intention to use instructional treatments; and 3) interaction levels with instructional treatments. The experimental research design of the study was a 3×2 randomized posttest design. Multivariate Analysis of Variance (MANOVA) was used to analyze collected data. The main effects and the potential interaction of the two independent variables were examined. Results indicate that the presentation of waveform variations and the change of parameters in the course content renders significant higher learning outcomes than online text-only materials and online texts with illustrations $(\mathrm{Lambda}\ (8, 248) = 0.637, p < 0.05)$.**

***Index Terms*—Digital-filter design, e-learning, human-computer interaction, virtual laboratory assessment.**

I. Introduction

Digital-filter design is typically designed to impart the concepts of digital signal processing, sampling theorem, Fourier transformation, convolution, Z transformation, infinite impulse response (IIR) filter, and finite impulse response (FIR) filter. This course involves complicated mathematical equations and dynamic waveform variations. From the perspective of computer-aided learning, software simulations designed as a virtual laboratory enhance students' active learning experience [1], encourage self-learning by providing hands-on exercises [2], [3], and improve the effectiveness and efficiency of engineering instruction and learning [4]–[6]. Previous studies in engineering education research have covered a variety of disciplines, such as chemical engineering [4], [7], computer engineering [8], electrical engineering [5], [9], and mechanical/aerospace engineering [2], [3], [10].

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In the field of digital-filter design, several previous studies developed computer software to simulate digital-filter design concepts. For example, Stouraitis and Taylor [11] developed a software package called DF-PAK for dual level courses such as digital-filter design; Turner *et al.* [12] developed a system, "DIGICAP," which allowed designers to evaluate the structures and implementation effect of different digital filters; Nielinger [13] simulated the digital IIR filter biquad section using PSPICE. Those studies focused on helping learners understand the concepts required in the digital-filter design course with the aid of a simulation system. However, they tended to create simulations for certain particular concepts, not for the course as a whole, which may ignore several important concepts, such as the fundamentals of digital signal processing, theory and architecture of digital filter, and design of digital filter. In addition, previous studies rarely investigated the impact of such a simulation system on student learning experience.

Two major problems were identified in reviewing current research in assessing virtual laboratories. First, assessment of irrelevant learning outcome variables: the majority of the current research focused on assessing student affective measures instead of evaluating genuine human learning performance as related to different types of learning objectives. Second, weak methodological design in conducting experimental research: most research used a relatively small sample size and also failed to validate the measurement instrument by reporting reliabilities of dependent measures.

This experimental study explored the effect of simulations in a virtual laboratory environment on engineering undergraduate students' learning achievement and attitude. Based upon the purpose of the study, three research null hypotheses may be drawn as follows.

1) No significant differences in student test achievement, intention, and interaction levels when they learn by using varied types of virtual laboratory instructional treatments.
2) No significant differences in student test achievement, intention, and interaction levels when they have different prior Internet experiences.
3) No significant interaction in student test achievement, intention, and interaction levels between the two studied independent variables: virtual laboratory instructional treatment and prior Internet experience.

II. Course Description

Digital-filter design is one of the most important topics in digital signal processing, a critical course in modern electronics/electrical engineering education. The content of the course can

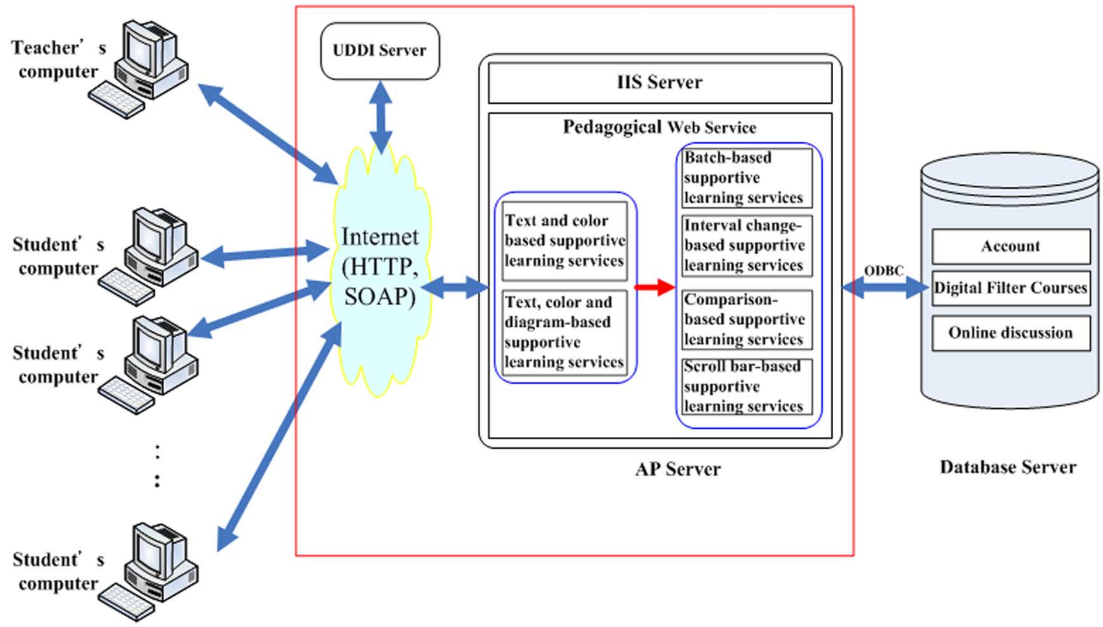

Fig. 1. System architecture.

be applied to a wide variety of fields, such as communication, medicine, control, robotics, and geophysics.

The content of the digital-filter design consists of fundamentals of a digital filter, structures of a digital filter, design of FIR, and IIR filters, applications of digital filters and tests, and feedback systems. Several related hands-on experiments are designed to help students apply their knowledge learned from the course content. According to the subject-matter experts who are currently teaching this course in the college, the course is divided into three major parts as briefly described below.

Part I: Basic concepts on analog and digital signals are introduced. In digital signal processing, an analog signal is transited through an analog-to-digital (A/D) translator. The main capability of an A/D translator is to transform an analog signal into a digital signal, after which, a digital-to-analog (D/A) translator is used to convert the result of a digital signal into an analog signal as its output.

Part II: The following theories in Digital Signal Processing (DSP) are introduced: convolution, sampling theory, discrete Fourier transform, and Z-transform. Then, basic principles and design methods of FIR filter and IIR filter follow. Several design examples are provided using MATLAB software simulations. For example, an experiment of filter architectures is conducted to convert coefficients from a direct form to a cascade form or a parallel form.

Part III: Based on the fundamental theories of FIR and IIR filters introduced in Part II, the most important characteristics of FIR filters are linear phase and position of zero, which are designed by Windows method and frequency sample method. Two main methods are introduced: 1) impulse invariant method; and 2) bilinear transform method. Finally, notch filters, comb filters, and all-pass filters are introduced. The results of output wave are obtained by using users' interface designed by MATLAB simulations.

Part II and Part III contain several virtual laboratory simulation experiments. In Part II, seven simulation experiments are conducted: 1) convolution; 2) sampling theory; 3) discrete Fourier transform; 4) Z-Transform; 5) FIR filter; 6) IIR filter; and 7) filter architectures transform. Part III contains eight simulation experiments: 1) linear phase method; 2) frequency sample method; 3) Windows method; 4) impulse invariant method; 5) bilinear transform method; 6) notch filter; 7) comb filter; and 8) all-pass filter. All the virtual laboratory simulation experiments are conducted by using MATLAB.

III. Virtual Laboratory Implementation

The system architecture of this virtual laboratory comprises four different modules: 1) End-user module; 2) Universal Description Discovery and Integration (UDDI) server; 3) Applications (AP) server; and 4) Database server (Fig. 1). The end-user module consists of the computers and browsers used by teachers and students. The UDDI server supports registration of Web services and service publishing via the Internet. The AP server provides IIS service and three virtual laboratory instructional treatments, namely, online text-only materials, online texts with illustrations, and online texts with simulations. The database server primarily stores and manages accounts created for teachers and students, keeps records of online discussions, and publishes digital instructional materials for the digital-filter course.

The three virtual laboratory instructional treatments in the AP server will be registered and published in the UDDI server. After the end-users receive their verification and authorization via Hypertext Transfer Protocol (HTTP) and Simple Object Access Protocol (SOAP), they can enter the AP server and then the database server can access the teaching and learning services they request. The services provided by the Web server are managed by the IIS server. Web services are managed by the AP

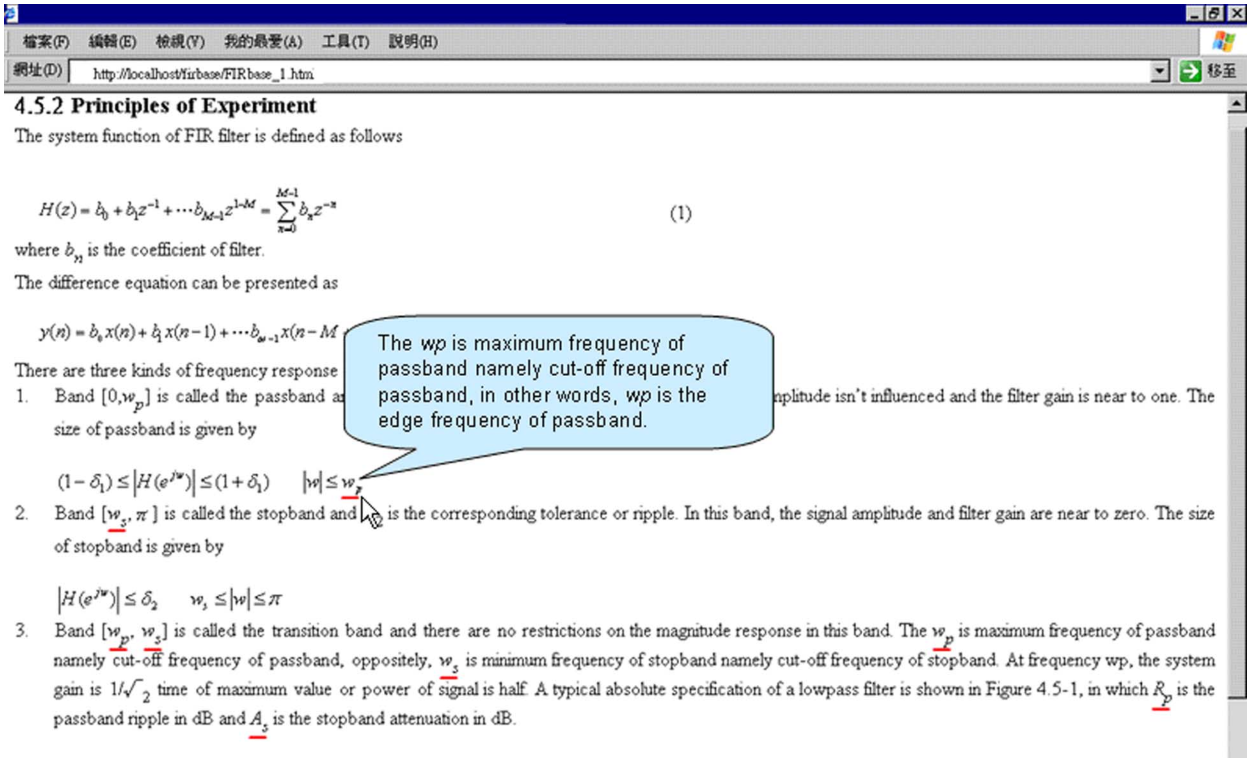

Fig. 2. Instructional treatment 1.

server that is connected to the database server via Open Database Connectivity (ODBC). The implementation of the Web services employs a MATLAB tool and the .NET from Microsoft to develop Web service solutions.

IV. Methods and Procedures

A. Participants

One hundred and thirty-three undergraduate students in a digital signal processing course participated in the study from the Electronic Engineering Department at the National Kaohsiung University of Applied Sciences (KUAS), Taiwan, R.O.C. Out of the participants, 125 (94%) were male; eight (6%) were female. Their age levels ranged from 21 to 23.

B. Instructional Materials

One instructional unit in the course, Introduction to Digital Filter, was used to conduct the experiment. This instructional unit covered FIR filter and IIR filter.

C. Independent/Dependent Variables

Two independent variables were studied: 1) instructional treatments (online text-only materials, online texts with illustrations, and online texts with simulations); and 2) prior Internet experience (high and low). Three dependent variables were measured: 1) a knowledge achievement test; 2) intention to use instructional treatments; and 3) interaction levels with instructional treatments. A knowledge test was given after students learned from the assigned experimental treatments. A questionnaire was designed to measure these two student affective constructs: 1) intention to use instructional treatments; and 2) interaction levels with instructional treatments. These two affective constructs were measured by a seven-point Likert scale. The Cronbach's alpha reliability coefficient is .903 for the 13-item questionnaire [see Appendix]. In order to guarantee the validity of the three dependent measures, the test items and the questionnaire were reviewed by subject matter experts.

D. Research Design

The research design of the study was a 3×2 randomized posttest design. Multivariate Analysis of Variance (MANOVA) was used to analyze collected data. The main effects and the potential interaction of the two independent variables were examined. Where significant F-values were found, pair-wise multiple comparison tests were performed by using the method of Tukey's Honestly Significant Difference (HDS) [14].

E. Instructional Treatments

Treatment 1 (control group): This treatment entailed the presentation of text-only materials on a HTML Web page. Participants accessed the instructional materials by using a scrolling browser (Fig. 2).

Treatment 2: On top of the treatment 1, this treatment added several static waveform illustrations. Fig. 3 illustrates the FIR waveform and depicts further the relationship among parameters w_p, w_s, R_p, and A_s and the width and height of corresponding waveforms.

Treatment 3: This treatment allowed students to run simulations by changing dynamic-filter parameters. The resulting waveforms would help them better understand the variations of waveform under different parametric values. Fig. 4 shows the

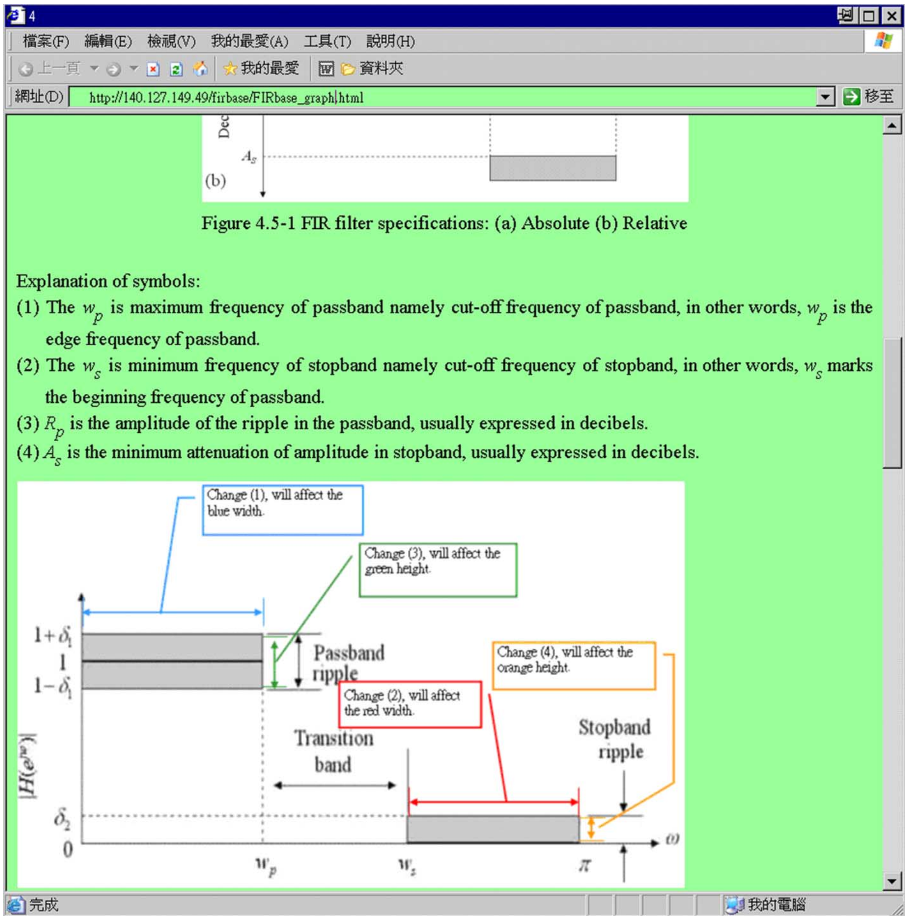

Fig. 3. Instructional treatment 2.

input of four parameters (w_p, w_s, R_p, and A_s) and the resulting waveform magnitude, magnitude in dB, and impulse.

F. Experimental Procedures

The student participants answered a seven-point Likert-type question about their Internet experience before they were assigned different instructional treatment groups. Based on the result of the question, they were divided into two groups of high and low prior Internet uses (56 and 77 students in each, respectively). To avoid potential sampling bias, a stratified sampling method was used to assign students randomly into instructional treatment groups.

After being arranged into their assigned experimental groups, the participants were allowed to have 45 minutes to complete the virtual laboratory treatments. After finishing the virtual laboratories, the participants were asked to take their criterion posttest and the questionnaire.

V. RESULTS

A. Results of MANOVA

The multivariate analysis of variance resulted in a Wilks' Lambda value [14] that would determine whether independent variables and their interaction had any effect on dependent variables. Table I showed that for the effect of interaction between virtual laboratory treatments and prior Internet use, the value of Wilks' Lambda was .927, with 8 and 248 degrees of freedom, which was not significant at the p-value of 0.05 ($\mathrm{p} = 0.302$). This result failed to reject null hypothesis 3 in the study. Similarly, the effect of prior Internet use on dependent measures did not yield any significant differences ($\mathrm{p} = 0.104$). Therefore, the null hypothesis 2 should not be rejected.

However, a significant effect of virtual laboratory treatments was found ($\mathrm{Lambda}\ (8, 248) = 0.637, \mathrm{p} < 0.05$). The univariate analysis of variance resulted in an F-ratio that was used to determine whether variations in the performance on the dependent measures were influenced by the various treatments and levels of prior Internet use. The detailed results are explained as follows.

Hypothesis 1 investigated the treatment effect of virtual laboratory treatments. An analysis of variance was conducted for each of the three dependent measures. The results from these three dependent measures are reported as follows.

- *Dependent Measure 1: Knowledge test*

The analysis of variance for the knowledge test showed that significant differences among treatment groups existed ($\mathrm{F}[2, 127] = 13.59, \mathrm{p} < 0.05$). Therefore, for the knowledge test, hypothesis 1 was rejected at the 0.05 level.

Since significant differences existed in the knowledge test, the follow-up Tukey's HDS was conducted to determine where the differences came from among the treatment groups. Table II showed that significant differences were discovered between

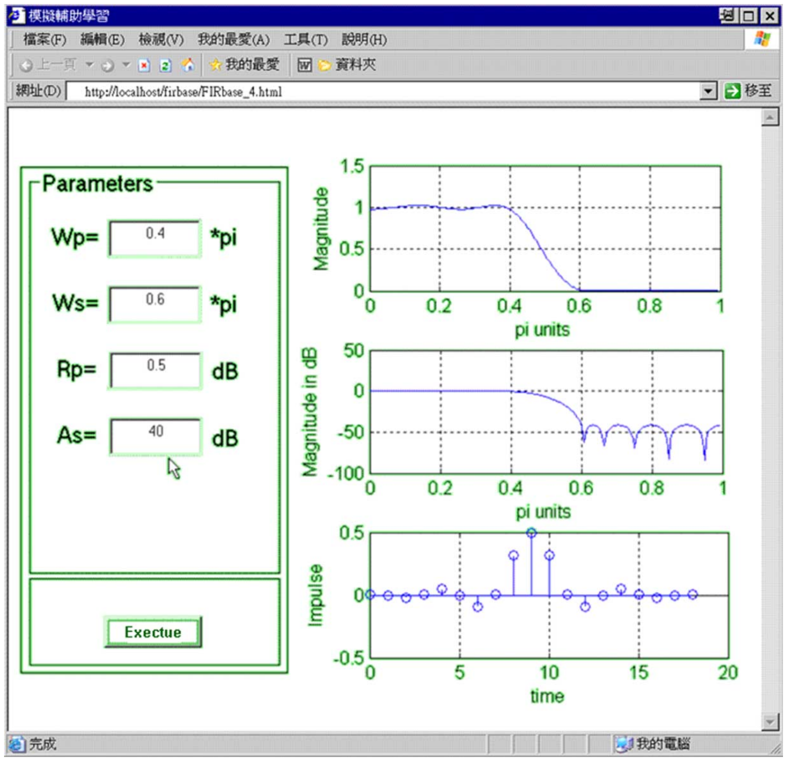

Fig. 4. Instructional treatment 3.

TABLE I
MULTIVARIATE TESTS

Effects	Wilks Lambda	F	P
Prior Internet Use	.940	1.966	.104
Treatment	.637	7.852	.000*
Interaction	.927	1.196	.302

* Significant at 0.05 level F: F ratio; p: p value

TABLE II
TUKEY HDS FOR KNOWLEDGE TEST

Source	Mean Diff.	Std. Err.	Sig.
Treatments 1 & 2	-6.67	4.024	.100
Treatments 1 & 3	-20.95*	4.076	.000*
Treatments 2 & 3	-14.28	4.204	.001*

*Significant at .05 level

TABLE III
TUKEY HDS FOR INTENTION MEASURE

Source	Mean Diff.	Std. Err.	Sig.
Treatments 1 & 2	-.84	.264	.002*
Treatments 1 & 3	-1.19*	.267	.000*
Treatments 2 & 3	-.34	.276	.214

*Significant at .05 level

TABLE IV
TUKEY HDS FOR INTERACTION MEASURE

Source	Mean Diff.	Std. Err.	Sig.
Treatments 1 & 2	-.249	.197	.209
Treatments 1 & 3	-.576*	.200	.005*
Treatments 2 & 3	-.327	.206	.115

*Significant at .05 level

treatment 1 (online text-only materials) and treatment 3 (online texts plus simulations), and between treatment 2 (online texts plus illustrations) and treatment 3. However, no significant differences occurred between the treatment 1 and treatment 2.

- *Dependent Measure 2: Intention to use virtual laboratory treatments*

The analysis of variance for the Intention measure showed that significant differences among treatment groups existed ($\mathrm{F}[2,127] = 11.045, \mathrm{p} < 0.05$). Therefore, for the Intention measure, hypothesis 1 was rejected at the 0.05 level.

The Tukey HDS indicated that significant differences existed between treatment 1 and treatment 2, and between treatment 1 and treatment 3. However, no significant differences were found between treatment 2 and treatment 3 (Table III).

- *Dependent Measure 3: Interaction levels with virtual laboratory treatments*

The analysis of variance for the Interaction measure showed that significant differences among treatment groups existed ($\mathrm{F}[2,127] = 4.793, \mathrm{p} < 0.05$). Therefore, for the Interaction measure, hypothesis 1 was also rejected at the 0.05 level.

Table IV indicated that there were significant differences between treatment 1 and treatment 3. However, no significant differences existed between treatment 1 and treatment 2, or between treatment 2 and treatment 3.

- *Summary of Hypothesis 1 Test*

Statistical results showed significant differences in students' dependent measures among the three virtual laboratory treatments. Specifically, regardless of levels of prior Internet experiences, treatment 3 (online texts plus simulations) was superior to treatment 1 (online text-only materials) for all the

TABLE V
SUMMARY OF HYPOTHESIS 1 TEST

Tests	Null Hypothesis 1
Knowledge test	Rejected (T3>T1; T3>T2)*
Intention measure	Rejected (T3>T1; T2>T1)*
Interaction measure	Rejected (T3>T1)*

*Significant at .05 level; T: Treatment

dependent measures (knowledge test, Intention, and Interaction measures). In addition, treatment 2 (online texts plus illustrations) was significantly better than treatment 1 on the Intention measure. Treatment 3 was significantly better than treatment 2 on the knowledge test. Thus, the conclusion is that this null hypothesis 1 should be rejected. Table V summarizes the results of the statistical testing of hypothesis 1.

VI. CONCLUSION

From the previous findings, if not considering extraneous variables, one may conclude that the virtual laboratory with simulations improves students' achievement in learning digital-filter design. In other words, the presentation of dynamic waveform variations along with the change of parameters renders significant higher learning outcomes than online text-only materials and online texts with static illustrations. In addition, the students in the MATLAB simulation group expressed a significantly higher intention to learn in such an environment than in an online text-only environment. They also felt that learning in a simulation environment created more interactions between students and the virtual laboratory treatment. These results are consistent with Clark and Mayer's assertion [15] that process information is effectively visualized with animations/simulations. In fact, simulations make it easier to observe differences among varied waveforms when assumed parameters change. In terms of usability [16], such results reflect the attributes of virtual laboratory simulations. They are easy to learn, efficient to use, and easy to remember.

While students found online texts with static illustrations were more interesting to learn than the text-only group, their learning achievements did not yield significant differences. One of the potential explanations is that the static illustrations along with the online texts in digital-filter design content are too complex to comprehend. Those complex illustrations may need further clarification by using other effective instructional strategies.

This experimental study provided a framework of assessing virtual laboratory simulations by involving human participants. According to the findings of the study, future research should continue to investigate the impact of virtual laboratory environments on students' learning achievement, especially on their higher order cognitive abilities, such as comprehension, problem-solving, and critical-thinking skills. Additionally, future studies should consider more human factors in such a learning environment, such as learners' individual differences, learning styles, preferences in learning visual/audio materials, etc. Many of the independent variables associated with the study of aptitude-treatment interactions should be taken into account in the design of virtual laboratories.

While virtual laboratory simulations may be manipulated to influence students' learning positively, particular attention must be given to guidelines derived from learning with simulations and experimental methodology, and consideration of learner characteristics and learning styles. Only by initiating a systematic program of investigation where independent variables are judiciously manipulated to determine their relative effectiveness and efficiency of facilitating specifically designated learning objectives will the true potential inherent in virtual laboratory simulations be realized.

APPENDIX

The respondents need to answer the following questions in the seven-point Likert Scale, i.e., score 7 if you strongly agree with the statement, 4 if you neither agree nor disagree, and 1 if you strongly disagree.

1) I find that *virtual laboratory simulation* allowed flexible interactions.
2) I interacted with *virtual laboratory simulation* in a clear and comprehensible manner.
3) My interactions with *virtual laboratory simulation* did not require much effort on my part.
4) I find *virtual laboratory simulation* easy to use.
5) I find it easy to access the knowledge I needed from *virtual laboratory simulation*.
6) Using *virtual laboratory simulation* gave me more incentive to learn.
7) Using *virtual laboratory simulation* added to the fun of learning.
8) Using *virtual laboratory simulation* improved my learning experience.
9) Using *virtual laboratory simulation* enhanced my knowledge and skills.
10) Using *virtual laboratory simulation* enhanced the effectiveness in learning.
11) I find the *virtual laboratory simulation* useful for learning the course.
12) If I have access to *virtual laboratory simulation*, I have the intention to use it.
13) When I have access to *virtual laboratory simulation*, I expect to make use of it.

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