Instructional Module in Fourier Spectral Analysis, Based on Principles of "How People Learn"

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ABSTRACT

This paper describes the design and evaluation of an instructional module for teaching/learning Fourier spectral analysis, with emphasis on biomedical applications. The module is based on the principles of "How People Learn" (HPL) as embodied in the Legacy cycle. This cycle is a particular instantiation of problem-based learning and includes components explicitly aimed at providing context and motivation, facilitating exploration, developing in-depth understanding, and incorporating opportunities for self-assessment. In the spectral analysis module, traditional teaching methods are augmented with small group discussions, peer-to-peer learning, a Web-based tutorial, and an interactive demonstration. Assessment included the development of rubrics for scoring student understanding of key concepts, revealing that students who used the module demonstrated better understanding relative to students who studied the material using traditional methods. Survey results and comments indicate that students generally liked the interactive tutorial and demonstration, as well as the structure provided by the HPL framework.

I. INTRODUCTION

A. Motivation

Fourier spectral analysis is an important concept relevant to many electrical and biomedical engineering applications, including speech analysis, speech processing, magnetic resonance imaging, and analysis of biomedical signals such as the electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG). The motivation for developing this module comes from the first author's experiences teaching spectral analysis for six years in a graduate-level course entitled *Biomedical Signal and Image Processing*. Many students in this class had difficulty mastering the fundamentals of spectral analysis, appearing to be overwhelmed by the interaction of multiple variables. Results from lab reports indicated that even students who did master the fundamentals typically did not apply them, instead they managed to succeed in the lab exercises by fiddling with parameters. These experiences motivated the development of a module to assist students both in learning the fundamentals of Fourier spectral analysis and in applying those concepts to biomedical applications.

B. Pedagogical Framework

The instructional module described in this work is based on principles of "How People Learn" (HPL) [1], which specifies four qualities of effective learning environments:

1. *Learner-centered* environments consider students' previous experiences and prior knowledge as a basis for future learning.
2. *Knowledge-centered* environments present new material with the rationale for studying the topic and with relevant connections to other topics, in order to facilitate understanding, to develop accessible knowledge that can be applied appropriately, and to promote transfer of concepts to new situations.
3. *Assessment-centered* environments include opportunities for self-assessment, feedback, and revision.
4. *Community-centered* environments increase students' opportunities and motivation to interact with faculty and peers, receive feedback, and learn.

The Legacy cycle [2, 3] provides one possible approach for designing learning environments that incorporate the elements of HPL. It can be viewed as a particular instantiation of problem-based learning. The major steps of the Legacy cycle are:

1. *The Challenge* poses a complex goal to motivate students and to provide them with opportunities to explore new material by exercising problem solving and inquiry skills.
2. *Generating Ideas* allows students to explore their initial thoughts about the challenge, making explicit and documenting any naïve preconceptions or misconceptions.
3. *Multiple Perspectives* provide expert insights, exposing students to advanced thinking on multiple aspects of the challenge, without providing a direct solution.
4. *Research and Revise* consists of resources and learning activities that help students develop expertise to effectively approach multiple aspects of the challenge.
5. *Test your Mettle* consists of opportunities for formative assessment, allowing students to reflect on what they have learned and to identify any weaknesses in their current understanding.
6. *Go Public* is the final, summative assessment of students' understanding of the material at the end of the module.

The Legacy cycle has proven quite versatile and has been applied to the design of instructional modules used in contexts ranging from elementary to post-graduate education, spanning time frames ranging from a few hours of class time to semester-long projects. The spectral analysis module described in Section II exemplifies how the HPL framework can be applied to material covered in a few hours of an advanced-undergraduate or graduate subject.

II. Design of the Instructional Module

The objective of the module as an educational innovation is to help students master the fundamentals of Fourier spectral analysis, ultimately increasing the number of students who obtain a working understanding of the topic. The design process began by specifying the learning objectives and key concepts for the module. The major learning objective is that students should be able to analyze the frequency content of an arbitrary signal and to interpret a given frequency representation. Key concepts underlying this objective include effect of window length, window shape, and discrete Fourier transform (DFT) length on both frequency resolution and amplitude resolution. These objectives and concepts subsequently guided the technical content authored for the module.

The traditional methods of teaching spectral analysis (lectures, lab exercises, and homework problems) were reorganized in accordance with the Legacy cycle and augmented by additional elements, as described in Section II-A. The additional elements include an interactive demonstration of spectral analysis and a Web-based tutorial, described in Sections II-B and II-C, respectively. The reorganization of existing educational materials reduced development effort, and the addition of new elements provided students with a wide variety of learning environments.

Traditionally, the fundamentals of Fourier spectral analysis were covered in one ninety-minute lecture. An additional lecture on cardiac electrophysiology provided background for a four-hour lab exercise on the application of spectral analysis to ventricular arrhythmia detection. The new components introduced by the HPL framework require two hours of class time and another two hours of preparation time; this was accomplished by using an additional four-hour lab session.

A. Legacy Cycle

In this module, the components of the Legacy model are as follows:

1. *The challenge* is to design a system for monitoring a patient's ECG signals in a hospital setting. The system should sound an alarm when a life-threatening ventricular arrhythmia occurs. While failure to detect an arrhythmia is obviously undesirable, false alarms are also quite problematic, as hospital staff may ignore systems with frequent false alarms. The background for this challenge is introduced in a lecture on cardiac electrophysiology. The actual design challenge is described in the lab handout that students are expected to read before coming to lab, and it is presented by the instructor at the start of a lab session.
2. Immediately following presentation of the challenge in lab, students break up into small groups (of two or three) to *generate ideas.* They discuss how to approach the challenge, based on their preliminary understanding of spectral analysis. Each group prepares their ideas as an informal presentation for the other groups in their lab session.
3. Next, the larger group reconvenes to hear *multiple perspectives.* Each small group presents their ideas. Depending on the breadth of ideas presented, the instructor may also introduce additional perspectives. The instructor then solicits student reactions to the various ideas and moderates a discussion to identify their strengths and weaknesses. The instructor may also provide expert reactions and insights to the students' ideas and perspectives.
4. Students *research* spectral analysis and *revise* their understanding by using novel interactive exercises developed for this module and by attending the spectral analysis lecture. The interactive exercises consist of a Web-based tutorial accompanied by an interactive demonstration of spectral analysis, as described in Sections II-B and II-C. Use of these materials began in the same lab session used for items 1–3 above, but the materials remained available to students for continued use outside of class. The spectral analysis lecture is essentially the same lecture used previously, but in the past it was the students' first exposure to the topic. In the current module, it is delivered after students have been exposed to spectral analysis and have had extensive hands-on experience with the on-line exercises. It is expected that the later placement of the lecture will allow students to further revise their developing understanding of spectral analysis.
5. Students *test their mettle* using two previously existing instructional materials. Homework problems provide one opportunity for students to apply what they have learned about spectral analysis in slightly different contexts. In addition, students attempt to solve the cardiac monitoring challenge during a full lab session the following week. This is done in groups of two, which provides opportunities for peer-to-peer learning.
6. Students *go public* using two previously existing assessment tools, the lab report and the quiz. Although students work with a partner in solving the challenge in lab, each student writes his/her own report.

B. Interactive Demonstration of Spectral Analysis

The purpose of this on-line demonstration is to allow students to engage and interact directly with the key variables in the spectral analysis processing. Such hands-on experiences are expected to improve students' conceptual and intuitive understanding of theoretical concepts [4]. The interactive demonstration [5] utilizes the MATLAB® Web Server to perform spectral analysis of cosine, ECG, and speech signals.

The input window displays a block diagram illustrating the steps of the processing and allows user selection of key parameters such as window length, window shape, and DFT length. The output window displays the results of the processing, as well as intermediate results that illustrate the effects of individual processing steps. Additional options permit the user to compare and contrast multiple parameter sets and also to generate spectrograms when the input is a speech signal. In addition to its central role in the Web-based tutorial, the interactive demonstration is used in class during the spectral analysis lecture.

C. Web-based Tutorial

The goal of the Web-based tutorial is to guide students as they develop an understanding of key concepts in spectral analysis. The tutorial consists of a series of questions (true/false, multiple choice, and short answer), accompanied by links to resources that may be useful in answering the questions. These resources include general text summaries of key concepts, a glossary of terms, tables, figures, hints specific to a particular question, tips for using the interactive demonstration, and the interactive demonstration itself.

Some of the tutorial questions explicitly direct students to use the interactive demonstration in certain ways, especially for comparing and contrasting different parameter selections. Other tutorial questions may be answered with or without optional use of the interactive demonstration. After responding to a question, the student has the option of checking his or her answer, accessing hints and other resources for review as necessary, and then trying again. After the student has settled on a final answer, he or she may view the correct answer and an explanation.

The tutorial questions encourage constructive use of the interactive demonstration and stimulate student exploration. If the interactive demonstration were provided independently, without the framework of the tutorial as a specific assignment, students would be unlikely to make productive use of the interactive demonstration [6]. Together, the tutorial and demonstration constitute an interactive exercise that keeps students active and involved with the material, a prerequisite for effective learning [7].

III. Methods

A study was performed in order to assess the effect of the module. Instructors at the Harvard-MIT Division of Health Sciences and Technology (HST) taught Fourier spectral analysis without the module one year, and with the module the following year, collecting relevant data about student understanding of the material as well as subjective student reactions. A rubric was developed to rate student understanding of key concepts in spectral analysis. The rubric was applied as part of a scoring procedure that was designed to: 1) allow comparison across years when different quiz questions were used; 2) reduce potential bias of the instructor/module developer; and 3) neutralize differences in scoring due to shifting standards of the instructor between years.

A. Delivery of Module

The spectral analysis module was developed for initial use in a semester-long course in Biomedical Signal and Image Processing (HST582) offered by the Harvard-MIT Division of Health Sciences and Technology. This is a graduate-level course, with a prerequisite of one semester of undergraduate signals and systems. The students are typically senior undergraduates and first-year graduate students from a variety of technical backgrounds, including electrical engineering, computer science, mechanical engineering, nuclear engineering, and aeronautics and astronautics. The course is offered yearly, and enrollment is typically 20–35 students. Students attend two ninety-minute lectures and one four-hour lab session each week.

During the spring term 2000, 27 students enrolled in the course (comparison group) and studied the spectral analysis material presented in the traditional manner, according to the time-line shown in Table 1. During the spring term 2001, 22 students (treatment group) studied the material with the module as described in Section II, which was delivered according to the time-line shown in Table 2.

	Tuesday	Wednesday/Friday	Thursday
Week 2	DTFT lecture	ECG lab part 1 - digital filters	ECG guest lecture
Week 3	Spectral Analysis lecture	ECG lab part 2 - arrhythmia detection	(unrelated lecture)
Week 4	No class	(unrelated lab)	DFT lecture ECG lab reports due
Week 5	(unrelated lecture)	(unrelated lab)	(unrelated lecture)
Week 6	(unrelated lecture)	(unrelated lab)	(unrelated lecture)
Week 7	(unrelated lecture)	No lab	Quiz

Table 1. Timing for presentation of material related to spectral analysis during Spring 2000, beginning with Week 2 of the term. Students attend lab sessions on either Wednesday or Friday. DTFT refers to the Discrete-Time Fourier Transform.

	Tuesday	Wednesday/Friday	Thursday
Week 2	ECG guest lecture	ECG lab part 1 - digital filters	DTFT lecture
Week 3	No class	ECG lab part 2 – HPL components (described in Section II-A, items 1-4)	DFT lecture
Week 4	Spectral analysis lecture	ECG lab part 3 - arrhythmia detection	(unrelated lecture)
Week 5	(unrelated lecture)	(unrelated lab)	(unrelated lecture) ECG lab reports due
Week 6	(unrelated lecture)	(unrelated lab)	Quiz

Table 2. As in Table 1, for Spring 2001.

Note that an additional four-hour lab session was devoted to the material in 2001.

B. Assessment Items

Two elements of *Going Public* intended for summative assessment of student learning were also used to assess the efficacy of the instructional module. The first was an open-ended question that students answered as part of their lab report:

> *Explain your choice of parameters (window length, window shape, and FFT length) used with the spectrum function. What is the effective frequency resolution (in Hz) of the spectral analysis that you performed?*

(Note that in this context, the term *FFT length* is interchangeable with *DFT length.*) Twenty-four of the 27 students in the comparison group included an answer to this question in their lab reports, while all of the 22 students in the treatment group responded. The second assessment item was a quiz question on the topic of spectral analysis. A different quiz question was used each year. All of the students in both groups attempted to answer the quiz question. The lab reports and quizzes were photocopied, graded, and returned to the students.

C. Rubrics

The original grading of the lab reports and quizzes was not useful for reliable module assessment. To provide consistency, a general rubric was developed by the first author and validated by a third-year graduate student who had expertise with the technical material but was naïve with respect to the research study assessing the instructional module. The rubric covers thirteen categories (described below) and consists of a proficiency scale, grading criteria, and descriptions with examples for each category and proficiency level.

The following five-point proficiency scale was used to capture the different levels of understanding that could be discerned from the student responses:

- 3—demonstrated excellent understanding
- 2—demonstrated adequate understanding
- 1—demonstrated partial understanding
- 0—did not address
- −1—demonstrated misunderstanding

The categories were based on three key concepts in spectral analysis, the effect of window length, the effect of window shape, and the effect of DFT length. For the lab question, students could potentially address each key concept both qualitatively and quantitatively, resulting in six categories. For the quiz questions, the categories were based on the same three key concepts, but with two categories per concept reflecting understanding of the concept itself and proper use of the related terminology. A seventh category was included to cover the computational portion of each of the quiz questions, which concerned time and frequency sampling. The thirteen categories are listed in Table 3.

Individual scoring criteria were generated for each of the thirteen categories being assessed. The overall rubric is a list of descriptions of answers with exemplars of student responses for each category and proficiency level. Some categories exhibited a subset of the five-point proficiency scale, that is, some categories did not have responses corresponding to ratings of 3 (excellent understanding) and/or 1 (partial understanding). Excerpts from the rubric for the lab report question are provided in the Appendix.

D. Scoring Procedure

Using the rubric described in the previous section to provide uniform criteria, two scorers regraded the student responses. The two scorers were the first author and a first-year graduate student, who had expertise with the technical material but was naïve with respect to the research study assessing the instructional module. Each scorer independently assigned a proficiency rating for every student and category. Ratings assigned by the two scorers were compared. Exact agreement between the two scorers was obtained in 79% of the items. When scores were mismatched by one proficiency level, the score given by the first author was used. When scores were mismatched by two or more levels, the two scorers discussed the response and reached an agreement. These

Category	***Inter-rater reliability***	***Z***	***Significance***
Lab Window Length Qualitative	0.78	-0.56	p = 0.58
Lab Window Length Quantitative	0.56	-3.34	**p < 0.001**
Lab Window Shape Qualitative	0.93	-3.95	**p < 0.0001**
Lab Window Shape Quantitative	0.75	-3.85	**p < 0.0001**
Lab DFT Length Qualitative	0.74	-2.58	**p < 0.01**
Lab DFT Length Quantitative	0.60	-1.47	p = 0.14
Quiz Window Length Concept	0.80	-1.41	p = 0.16
Quiz Window Length Terminology	0.65	-1.57	p = 0.12
Quiz Window Shape Concept	0.75	-3.89	**p < 0.0001**
Quiz Window Shape Terminology	0.81	-3.47	**p < 0.001**
Quiz DFT Length Concept	0.87	-1.46	p = 0.14
Quiz DFT Length Terminology	0.76	-1.94	**p < 0.05**
Quiz Computation	0.92	-1.57	p = 0.12

Table 3. Inter-rater reliability and results of Mann-Whitney U-test. Statistically significant differences are shown in bold type.

discussions also provided useful feedback for future revisions of the rubric.

IV. RESULTS

A. Student Understanding of Key Concepts

The inter-rater reliability was calculated for the two scorers before resolution of discrepancies. As shown in Table 3, the reliability values ranged from 0.56 to 0.92. A Mann-Whitney U-test [8] of the final ratings compared ordinal differences between groups (see Table 3). The Z-statistic indicates the divergence (in standard deviations) from the null hypothesis that there is no difference between comparison and treatment groups. In seven of the thirteen categories, students in the treatment group demonstrated significantly better understanding than students in the comparison group; there were no significant differences in the remaining six categories.

Based on a conceptually-guided Exploratory Factor Analysis, eleven of the thirteen categories were arranged into four groupings, as listed in Table 4. Three groupings were relatively reliable as measured by Cronbach's alpha [9]. Chronbach's alpha is a correlation-based measure of internal reliability that indicates the degree to which the set of component items relate to the same concept; values above 0.7 are considered representative of internal reliability. The *Quiz DFT Grouping* is somewhat less reliable but does have modest utility as a grouping. The remaining two categories (*Lab Window Length Qualitative and Quiz DFT Length Terminology*) substantially reduced the reliability of the concept groupings and were therefore examined independently.

Composite scores were computed for every student by summing the proficiency ratings of the categories comprising each concept grouping. In order to facilitate comparison of effect sizes between the different groupings, the composite scores (as well as ratings for the two categories not included in the groupings) were transformed to standard z-scores with zero mean and unit variance. A multivariate analysis of variance (MANOVA) compared the resulting z-scores for between-group effects. The results of the MANOVA are summarized in Table 4. The MANOVA also produced mean z-scores for each grouping/category adjusted to remove error attributable to other groupings/categories, shown in Figure 1. Students in the treatment group demonstrated significantly better understanding than students in the comparison group for three out of the four concept groupings and one of the two individual categories. There were no significant differences in the *Quiz DFT* grouping or the *Lab Window Length Qualitative* category.

Figure 2 compares the percentage of responses assigned to each proficiency ranking for each concept grouping and independent category. Responses by students in the treatment group generally received a greater percentage of ratings of "demonstrated adequate

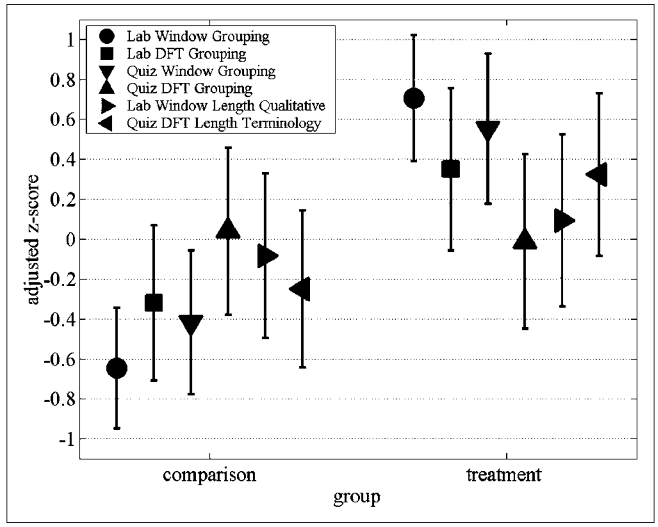

Figure 1. Relative effects between concept groupings within the treatment and comparison groups. The plot shows mean adjusted z-scores with error bars illustrating 95% confidence intervals.

Concept Grouping	Component Categories	Internal reliability	F-statistic	Significance
Lab Window Grouping	Lab Window Length Quantitative Lab Window Shape Qualitative Lab Window Shape Quantitative	0.76	38.27	**$p < 0.0001$**
Lab DFT Grouping	Lab DFT Length Qualitative Lab DFT Length Quantitative	0.77	5.66	**$p < 0.05$**
Quiz Window Grouping	Quiz Window Length Concept Quiz Window Length Terminology Quiz Window Shape Concept Quiz Window Shape Terminology	0.72	13.90	**$p < 0.001$**
Quiz DFT Grouping	Quiz DFT Length Concept Quiz Computation	0.49	0.03	$p = 0.86$
	Lab Window Length Qualitative	-	0.35	$p = 0.56$
	Quiz DFT Length Terminology	-	4.11	**$p < 0.05$**

Table 4. Organization of the thirteen categories into four groupings and two independent categories, with internal reliability of the groupings (as determined by Cronbach's alpha) and results of MANOVA. Statistically significant differences are shown in bold type.

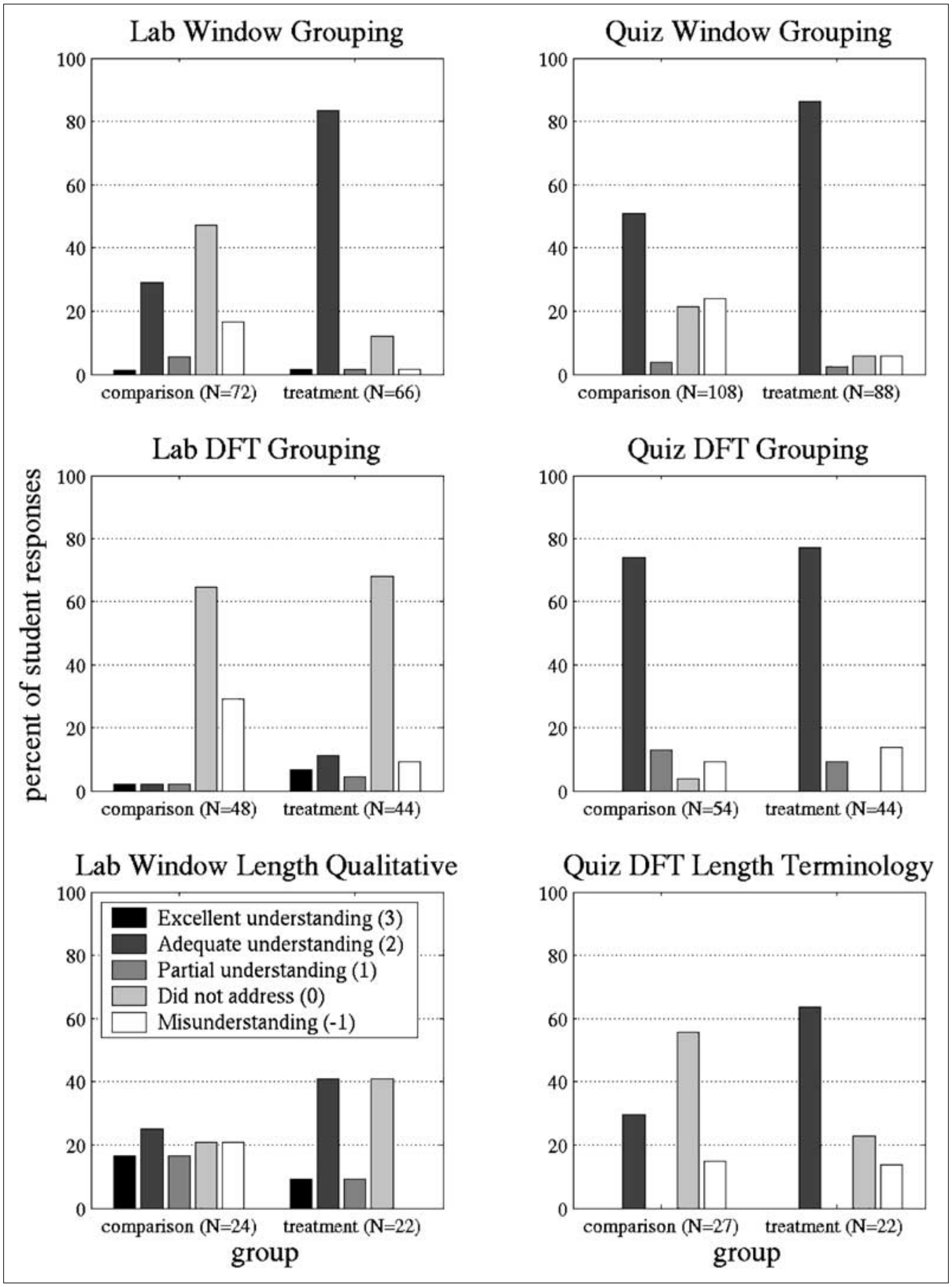

Figure 2. Percentage of student responses assigned to each proficiency ranking for the comparison and treatment groups, shown individually for each concept grouping and independent category. For each cluster of bars, N indicates the total number of student responses, which equals the number of participating students times the number of categories in that concept grouping.

understanding" and a smaller percentage of "did not address" and/or "demonstrated misunderstanding." This is consistent with the results in Figure 1 and Table 4. The difference is most dramatic in the two concept groupings showing the strongest statistical effects, the *Lab Window* grouping and the *Quiz Window* grouping. The difference is also strongly evident in the *Quiz DFT Length Terminology* category. The non-significant items, *Quiz DFT* grouping and *Lab Window Length Qualitative* category, do not show this trend. A milder trend is observed in the third statistically significant concept grouping, *Lab DFT*. The more modest trend for this category may be due to the substantial number of students in both the comparison and treatment groups who did not address the relevant concepts.

B. Subjective Impressions

Students' subjective impressions of module components were collected at several points throughout the term.

Positive: *"This was excellent. It was nice to be able to try things out and see for myself, rather than just be told. It made the material more clear."* *"With simple questions and immediate response, it helps significantly to clarify many concepts. With some repetitive questions, it is possible to remember what we learn, such as the comparison and contrast among all windows, etc."* *"I really liked the tutorial. I found it especially helpful that there were many questions focusing different aspects of the same fundamental concept. I think the level of understanding I gained from the tutorial far exceeds what I would have gained from reading or even doing a problem set during the same amount of time. The reason is that I was able to test my understanding repeatedly with instant feedback. I also like the \"check\" feature because it didn't immediately give away the right answer if I got something wrong. This enabled me to rethink the question and correct my own mistake. Another nice feature is that all the reference materials needed were readily available. It was easy to go back and re-read a section of the text to gain a better understanding. The interactive demo was OK but I didn't use it very much because I wanted to develop the intuition of what the response would be before running the virtual experiment. This tutorial is really awesome and I hope we use it more in the course!"*
Mixed: *"It was useful but it took too long, and I felt some questions were needlessly repetitive."* *"Questions were a bit too transparent (could answer them without truly understanding what's going on). And I would've liked more detailed explanations. But generally, this was a good exercise, and I'd like to see more of this type of instruction. Way to go!"*
Complaints/suggestions for improvement: *"Some parts are rather repetitive, but I guess that was the intent. A couple questions that I got wrong didn't have any sort of explanation, so that was a little unsatisfying."* *"The tutorial should include formulas and not rely on only demos for some questions"*

Table 5. Student comments on Web-based tutorial.

1) Tutorial Comments: As part of the final tutorial question, students were asked to type in their comments about any aspect of the tutorial. Because this was not anonymous, some students may have felt obligated to respond positively. Representative student comments are grouped into three categories and listed in Table 5.

2) End-of-term survey: On an anonymous end-of-term survey given in 2001, students used a five-point Likert scale to rate the usefulness of many aspects of the course. A rating of five corresponded to *extremely useful*, while a rating of one was labeled *complete waste of staff effort*. Three items on the survey directly addressed some novel components of the module: the interactive demonstration of spectral analysis; the tutorial questions, including hints and answers; and the tutorial resources, that is, text summaries, tables, and figures. Other items on the survey asked about the frequency with which students returned to use these materials later in the term.

Eighteen of the nineteen students responding to the survey rated all three of those components either four or five, indicating that they had found them useful. The one remaining student gave all three components a rating of two; that same student commented on the survey, "*Go over stuff more in class then go and do tutorial.*" Comments by the other students included the following: "*make more online tutorials*"; "*way cool*," referring to the interactive demonstration; and "*6," an attempt to give the interactive demonstration a rating of 6 on the 5 point scale. On another portion of the survey, 72% of students indicated that they returned, with varying frequency, to use the interactive demonstration and tutorial later in the term. One student wrote "*In preparation for the quiz it was very helpful*."

3) Lab Report Comments: As part of each lab report, students are asked to respond to the question "*What did you like/dislike the most about this lab exercise?*" The spring term 2000 responses to this question had not been retained. Instead, the spring term 2001 responses were compared between Lab 1 (the ECG lab which included portions of the spectral analysis module) and Lab 2 (a speech-coding lab which did not use the HPL framework, a Web-based tutorial, or the interactive demonstration).

In responding to this question on Lab 1, the majority of students commented on issues that are not directly relevant to the spectral analysis module. (This is because the question addresses the lab exercise, not the module; while the two intersect, neither encompasses the other.) Three students did specifically mention the tutorial, with one student commenting positively and two students giving mixed feedback, describing the tutorial as useful and interesting, but also tedious and disruptive to the flow of the lab exercise.

A fourth student wrote what could be considered a ringing endorsement of the HPL framework, though it should be noted that students were not given any information or instruction concerning the principles of HPL, the Legacy cycle, or the rationales behind the various pedagogical approaches used in class:

> *"I really liked the way this laboratory was organized. Designing a ventricular arrhythmia detector was not very hard after having solved the previous exercises that guided us through this task, which would have been otherwise hard to accomplish."*

Some very telling comments actually came in responding to this question on Lab 2, where four students made comparisons (either implicit or explicit) to Lab 1:

- *"Basically I just followed the lab instruction in this exercise. It's not so challenging as the first lab exercise. But I really enjoy the feeling of solving real-world problems using my knowledge."*
- *". . . I thought that a little more freedom in design of a coder decoder would be good."*
- *". . . at times, it seems a bit excessive to 'hold our hands' so much."*
- *"I liked the overall organization of the lab, but I would have done something a little differently. Instead of giving templates for all the code, I would have given a shorter lab assignment, but also less help. I think this way would make students learn better the details of the vocoders and of the way each Matlab function works."*

These responses were unexpected, as Lab 2 was unchanged from previous years and the instructor does not recall any such complaints in the past. Unfortunately, because student responses had not been saved the previous year, this is only anecdotal. Even so, it does appear that the HPL-informed module used in Lab 1 raised student expectations, and students were disappointed when those expectations were not met in Lab 2.

V. Discussion

A. Student Understanding

Results presented in Tables 3 and 4 and Figures 1 and 2 clearly show that students in the treatment group (who learned the material with the instructional module) obtained a better understanding of some key concepts than students in the comparison group (who did not use the module). We speculate that this is in part due to the Web-based tutorial's systematic presentation of individual variables and concepts, which had a mitigating effect on students' tendency to be overwhelmed by the interaction of multiple variables. The benefit of the instructional module is more pronounced for concepts related to window length and shape than for concepts related to DFT length. Future work should consider how to modify the tutorial in order to help students gain a better understanding of the concepts related to DFT length.

This improved understanding of Fourier spectral analysis must also be interpreted with two caveats. First, we developed the module during the summer and fall of 2000, after collecting the comparison data but before the treatment data. Significant faculty development occurred as a result of the module development process, which included explicit specification of learning objectives and key concepts. This unanticipated faculty development may have confounded our assessment. It is possible that the course instructor did a better job of teaching to the key concepts for the treatment group. Second, in order to accommodate the HPL framework, we added a four-hour lab session, doubling the amount of lab time spent on the topic. So, it is possible that better teaching and more class time contributed to the improved understanding demonstrated by students using the module.

B. Student Reaction to Module

Subjective student responses indicate general approval for the novel computer-based exercises used during *Research and Revise.* Students reported that they found the tutorial and demonstration useful, returned to use them later in the term for review, and wanted similar exercises for other material. Some students provided specific constructive criticisms that suggest ways to improve the tutorial and demonstration in the future.

A minority of students did not like the tutorial; they found it tedious and/or repetitious. We speculate that these complaints came from students with stronger backgrounds in the subject matter. Students who are initially more knowledgeable with regard to spectral analysis may not need the incremental presentation of the individual concepts used in the tutorial and may find the repetition tedious. However, other students commented on the repetition as a positive feature of the tutorial. These conflicting comments indicate the need for a more adaptive tutor, capable of providing a different sequence of questions depending on the student's demonstrated abilities. This is a trait of *intelligent tutoring systems*. Such systems include both a student model, reflecting the current state of the students' knowledge, and an instructional model, adjusting pedagogical strategies in response to the student model [7].

Although not truly adaptive, the current tutorial implementation did attempt to address differences in students' need for guidance by providing optional tips and hints associated with each question. We believe this approach may have been effective for students with weaker backgrounds by making additional help readily available. Of course it did not address the needs of more knowledgeable students, who would have preferred to cover the material more quickly.

C. HPL Framework

Evidence suggests that students (and teaching staff) reacted favorably to the HPL-informed aspects of the module. The basic principles of HPL represent a theoretical framework for designing successful learning environments, while the Legacy cycle provides one practical implementation of HPL that is related to problem-based and collaborative learning. Together, they can expedite the design of new instructional material or the improvement of existing materials. As evidenced by the current study, this HPL framework is also useful as a checklist for pedagogical problem solving. The traditional methods of teaching used in HST582J were acceptable by many standards (for example, generally positive responses on student course evaluations), yet many students struggled with the fundamentals of spectral analysis. Applying HPL was an effective way to "hone in" on the particular area where students were struggling and apply specific guidelines to improve the quality of instruction.

In our experience, HPL is particularly useful because it explicitly addresses many pedagogical issues that successful, experienced educators intuitively and implicitly incorporate in their instructional designs. In particular, the Legacy cycle employed here includes components explicitly aimed at providing context and motivation, facilitating exploration, developing in-depth understanding, and incorporating opportunities for self-assessment. Clearly any successful learning environment, whether HPL-based or not, should include these attributes. However, in traditional instructional design, these attributes are often ad hoc and consequently are delivered less effectively. The value of the HPL framework is that it makes explicit provisions for the elements of instruction that effective educators incorporate intuitively.

Student comments suggest that one successful aspect of the HPL-informed module is its ability to maintain an appropriate balance between design freedom and technical guidance. The challenge and ensuing activities motivated and engaged students while providing an opportunity for open-ended problem solving. (Recall that this was not replicated in Lab 2.) However, open-ended problem solving did not occur in isolation, as sometimes happens with projects assigned in engineering courses. The HPL framework produced a technically-supportive learning environment by combining learner- and knowledge-centered activities, in this case, the process of generating ideas, hearing multiple perspectives, and researching and revising one's understanding of the material. We speculate that the great appeal of the module is due to this combination of open-ended problem solving with concrete exercises to support the students' emerging understanding of the technical material.

VI. Conclusion

This paper described the design and evaluation of an instructional module for teaching/learning Fourier spectral analysis. The module is based on the principles of "How People Learn" (HPL) and uses a Legacy cycle where traditional teaching methods such as lecture and lab exercises are augmented with group discussions, a Web-based tutorial, and an interactive demonstration. The assessment included the development of rubrics for scoring student understanding of key concepts. Application of those rubrics revealed that students who used the module demonstrated better understanding of key concepts in spectral analysis relative to students who studied the material using traditional methods. This result must be interpreted carefully given the limitations of the study which included changes in the instructor's awareness of the key concepts and time-on-task in covering the material. Survey results and comments indicate that students generally liked the interactive tutorial and demonstration, as well as the structure provided by the HPL framework.

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APPENDIX

The following excerpts from the rubric used for scoring the lab report question deal with the two categories related to students' qualitative and quantitative understanding of the effect of window length.

Lab Window Length Qualitative

3. Indicates that window length is inversely related mainlobe width (this could be statement that longer window gives narrower mainlobe or shorter window gives wider mainlobe) and also indicates that mainlobe width determines frequency resolution.

2. Says that longer window length gives better frequency resolution (without mentioning mainlobe width) OR that longer window gives narrower mainlobe (without mentioning frequency resolution)

1. Stated that a chosen window length gave sufficient frequency resolution OR that window length is related to frequency resolution (without specifying how it's related)

0. Did not address window length qualitatively.

M. Confused window length with frame length OR Confused window length with FFT length OR explained that the window length was chosen to reduce fluctuations, for gradual transitions, or other incorrect reasoning

Lab Window Length Quantitative

3. Not used

2. Gives equation, or correct result of computation, for frequency resolution with constant in numerator and denominator equal to window length (or window length+1). Answer may be left in digital frequency (no units) or may be multiplied by Fs to get Hz.

1. Gives equation with window length in denominator, but also includes other incorrect factors in denominator related to FFT length. OR Computed digital frequency (without using Fs), but incorrectly assigned units of Hz.

0. Did not address window length quantitatively.

M. Confused window length with FFT length or frame length in equation OR gave incorrect value for frequency resolution with no explanation of computation.