The Magnitude Response Learning Game for DSP Education: A Case Study

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***Abstract*—Many topics of digital signal processing education are mathematically challenging while still being graspable by intuition – the task of the lecturer is to utilize the latter fact for the maximum benefit of the students. To this end, the Magnitude Response Learning Game (MRLG [1]) was introduced, a computer-based game teaching the connection between the pole/zero chart of a linear, time-invariant, discrete-time filter and its magnitude response. This paper presents the results of a statistical analysis of the game's effect on students' performance in related tasks, carried out at Graz University of Technology. While the qualitative results show that students are satisfied with the game and consider it a useful supplement to the available teaching material, the quantitative study suggests a strong positive correlation between the number of game rounds a student played and his/her performance in related tasks.**

***Index Terms*—DSP education, learning games, magnitude response, pole/zero charts**

I. Introduction

Gamification, i.e., the application of game-mechanics to non-game settings, has recently gained significant attention in higher education based on the observation that it can increase the motivation of students [2], [3]. For example, Iosup and Epema showed that the percentage of computer science students passing a course and their participation in voluntary activities increased by introducing game-elements in class [4]. Anderson et al. [5] proposed an online platform for teaching data science concepts: Students upload programming assignments, which after automatic evaluation are rewarded with badges. The majority of students expressed a positive attitude toward the platform. Lawrence [6] proposed to teach data structures by requiring students to program game intelligence for Critical Mass, a game conceptually similar to Go, Reversi, or Conway's Game of Life. Students had to programm a board evaluator, a move generator, and a game tree before they could challenge either computer bots or the game intelligence of other students. Rewards were given in terms of points for beating computer bots, and in terms of a leaderboard comparing students' performances. Again, the majority of students was satisfied with this teaching method. Ibáñez et al. [7] introduced a platform on which students could ask, assess, and answer questions related to C programming; the reward structure consisted of points, leaderboards, and badges. They found that the platform motivated students to continue learning even after achieving the best possible grades and concluded that students' understanding of C programming problems improved due to the introduction of the platform. Chaves et al. [8] recently showed that a game-based approach to support teaching of software process models is superior compared to project-based learning in terms of students' performance. In their tool, students had to name elements of a software process model. Correct solutions are rewarded by admitting the student to the next difficulty level.

While this list is far from exhaustive, it suggests that most effort for gamification has been done in the area of computer science. This suspicion is confirmed by a recent review [9], which also highlights the fact that most of the covered studies report positive effects of gamification.

In view of this vast body of literature suggesting the beneficial effects of gamification, we decided to use a computer-based learning game to supplement digital signal processing (DSP) education at Graz University of Technology. DSP education has been underrepresented in the literature on gamification so far. One exception is [10], in which the positive effect of playing a card game in a signal processing course was shown.

The computer-based learning game we used in DSP eduction at Graz University of Technology (see Section II), is the Magnitude Response Learning Game (MRLG, [1]). The magnitude response (e.g., [11, Ch. 5.1]) of a linear, time-invariant filter is the Fourier transform of its impulse response and, loosely speaking, describes the effect of the filter on the amplitude spectrum of a signal. For filters described by finite-order difference equations consisting of a recursive and a non-recursive part, the z-transform of the impulse response, i.e., the transfer function, is a ratio of polynomials. The complex roots of these polynomials constitute the pole/zero chart of the filter, which is tightly linked to the filter's magnitude response: The closer a zero (pole) is to the unit circle, the smaller (larger) is the magnitude response at the corresponding frequency, cf. [11, Ch. 5.3]. This connection admits drawing a magnitude response *qualitatively* based on the pole/zero chart only, which subsequently has become a common task in our classes, homeworks, and exams.

A deeper analysis of previous exams and homework submissions revealed that many students have problems drawing magnitude responses qualitatively. Non-zero minima are confused with zeros, maxima with poles, symmetries (for filters with real-valued coefficients) and periodicities (for discrete-time filters) are not recognized. Since the magnitude response

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is of paramount importance for the understanding of filters, these problems have to be dealt with. There exist multiple online- or computer-based tools teaching the connection between the pole/zero chart and the magnitude response, such as Signals and Systems Using Matlab [12], the online Java-based laboratory J-DSP [13], [14], or ZPGUI[1]. What, to the best of our knowledge, was missing until recently is a learning *game* dealing with this topic, making the process of learning both playful and motivating. The MRLG, introduced in [1] and briefly described in Section III, filled this gap.

The MRLG was designed to addresses the problems students encounter when drawing magnitude responses: In each of the relatively short rounds (10-30 seconds), students estimate a magnitude response based on a pole/zero chart. Immediately after subitting their estimate, the students see the true magnitude response superimposed on their estimate, together with a game score. To increase motivation, the students can compare their score with the average score on the game's webpage[2], which also displays leaderboards based on unique but anonymous player IDs. While the short duration of each round reduces the inhibition threshold, the revelation of the true magnitude response shall help the students gain a better intuition about the connection between the pole/zero chart of a filter and its magnitude response. We hence formulate the following hypothesis:

H1 Playing the MRLG has positive impact on the students' performance in drawing a magnitude response based on a pole/zero chart.

In order to test this hypothesis, we performed two online surveys (see Section IV) during which students had to match magnitude responses to a given pole/zero chart. While the first of these surveys was conducted immediately after introducing these concepts in class (pretest), the second survey took place after several weeks during which students had time to play the MRLG, and during which several related examples were worked through in class and during homeworks. To reduce the maturation effect, we asked the students to note the number of rounds they played: The statistical analysis is based on the improvement of students' performance *as a function of the number of played rounds*. As our results in Section V show, we could confirm hypothesis H1 by showing that students playing the MRLG often improve to a greater extend than students who did not play or played only a few rounds. Moreover, as the surveys and the course evaluation results show, students are generally in favor of the MRLG and wish to have more online- or computer-based learning games in class.

II. DSP Education at Graz University of Technology

At Graz University of Technology, bachelor students of electrical engineering, telematics, biomedical engineering, and audio engineering get exposed to digital signal processing in their fourth semester. The mandatory DSP course consists of a lecture (13-15 units, 90 minutes each) and accompanying problem classes (8 units, 90 minutes each; see Table I for class material). The lecture is graded through a three-hour exam which tests both theoretical knowledge and problem-solving capabilities. The problem classes are graded via delivery of four homework assignments on which the students can work in pairs. Homework assignments consist of both analytical and numerical problems, with a ratio of 2:1. Numerical problems are solved via computer algebra systems such as MATLAB and Octave. The last homework assignment contains a design challenge, and the winning student team gets awarded a small prize. In 2014, 324 students were registered with this course.

TABLE I
Course Material for the Problem Classes. A (*) indicates that this problem class was connected to magnitude responses and/or pole/zero charts.

1	Periodic signals, convolution
2*	Systems (linear and nonlinear, time-variant and time-invariant)
3	Fourier transforms
4	Fast Fourier transform
5*	z-transform, pole/zero charts, magnitude response
6*	Allpass, sampling & reconstruction
7	Filter structures, multi-rate signal processing
8*	Round-off noise, bilinear transform

While the lecture is held by the professor (in 2014, Gernot Kubin), the students can choose between four lecturers organizing the problem classes (in 2014, Bernhard C. Geiger, Pejman Mowlaee, Hannes Pessentheiner, and Sebastian Tschiatschek). In addition, study assistants organize question-and-answer sessions prior to homework delivery deadlines which students can attend on a voluntary basis. Outside these sessions, questions regarding the homework problems can be asked via a newsgroup, which is moderated by study assistants and lecturers. Both the lecture and the problem classes follow closely the textbook [11], covering (most parts of) Chapters 2-9 and 12.

As it is natural for a DSP course, the frequency/magnitude response of a discrete-time, linear, time-invariant filter is an important concept both in the lecture and in the problem classes. Relatively early in the course, students are taught the connection between the pole/zero chart of the transfer function and the filter's magnitude response. This knowledge is essential in understanding the behavior of linear filters in general, and the all-pass property and the minimum-phase/allpass decomposition in particular. Moreover, this connection gives the effects of filter coefficient quantization an intuitive dimension.

During previous evaluations, both the lecture and the problem classes received generally positive feedback, despite this course being one of the more demanding and work-intensive ones in the bachelor studies. A large part of this positive feedback is probably due to our multi-strategy teaching approach (direct instruction by professor and lecturers, interactive instruction during the question-and-answer session with our study assistants, and independent study during solving homework assignments). The introduction of the MRLG now adds another teaching strategy – experiential learning – to our portfolio.

[1] http://dadorran.wordpress.com/2012/04/07/zpgui/

[2] www.spsc.tugraz.at/content/magnitude-response-learning-game

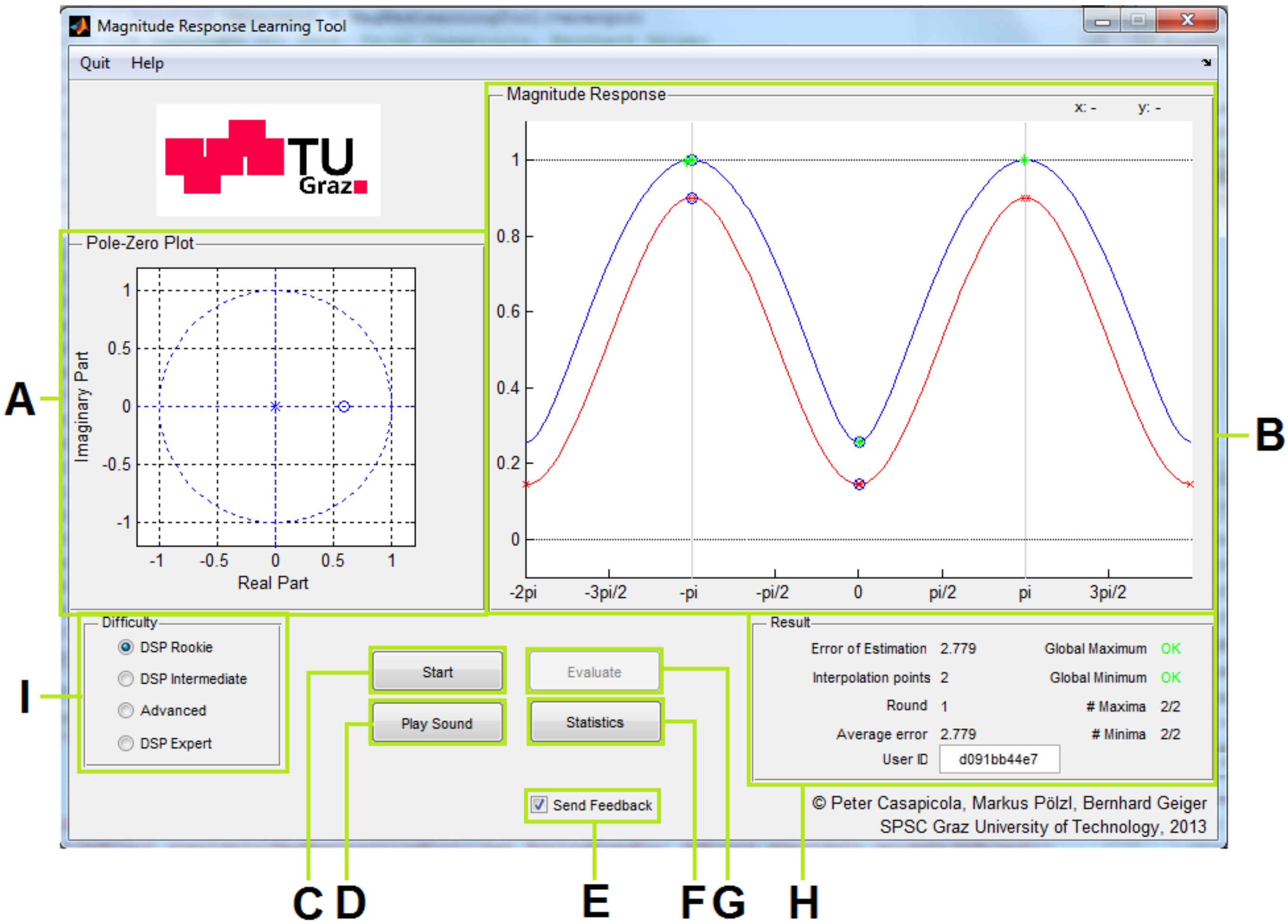

Fig. 1. Graphical User Interface of the Magnitude Response Learning Game (MRLG). (A) is the pole/zero chart of the predefined filter with the selected difficulty (I), and (B) is the area where the estimated magnitude response (red) can be drawn. A new round is started with (C), while (G) displays the true magnitude response (blue) and evaluates the current estimate; results are displayed in (H). (D) plays an audio file twice, once with and once without applying the filter depicted in (A). The results of each round are stored locally to allow a statistical evaluation (F); if the user permits (E), the results are also stored in an online database for usage statistics and player-vs-player comparisons. For a more detailed description, see [1].

III. Magnitude Response Learning Game

The MATLAB-based Magnitude Response Learning Game (MRLG) is learning game aimed at improving the students' understanding of the connection between the zeros and poles of a filter's transfer function and its magnitude response. As opposed to many other graphical user interfaces (GUIs) teaching this connection (e.g., Signals and Systems Using Matlab [12], DSP First [15], [16], various Mathematica tutorials [17], and the online Java-based laboratory J-DSP [13], [14]), our GUI is a game: Instead of being presented pole/zero charts and magnitude responses simultaneously, in each round of the game the player has to *estimate* the magnitude response from the given pole/zero chart. The player can do this by placing an arbitrary number of interpolation points in the magnitude response window (B) in Fig. 1. At the player's choice, the true magnitude response is displayed and the estimate is evaluated (button (G) in Fig. 1). The estimation error is, essentially, the noise gain of a system having a magnitude response equal to the difference between the true and the estimated magnitude response. This error, together with various other evaluation criteria, is stored on the player's computer and, optionally, in an online database hosted at Graz University of Technology. Fig. 2 shows a glimpse of the MRLG webpage, illustrating usage statistics and leaderboards based on the entries of the online database. In addition to that, with the help of a unique user ID, the webpage allows player-vs-player and player-vs-alltime average comparisons. For a more detailed description of the MRLG and the features of the webpage, the interested reader is referred to [1].

To address the problems students have when drawing magnitude responses, the MRLG features filters with four different difficulty levels: The first two difficulty levels contain filters with real-valued coefficients only, while the remaining two levels may feature complex filters as well. Both filters with zeros on the unit circle and filters with zeros close to the unit circle are available, trying to emphasize the difference between (local) minima and zeros in the magnitude response. Zeros and poles are placed at all possible angles inside the unit circle, requiring students to correctly place the corresponding extrema not only on the ordinate, but also on the abscissa

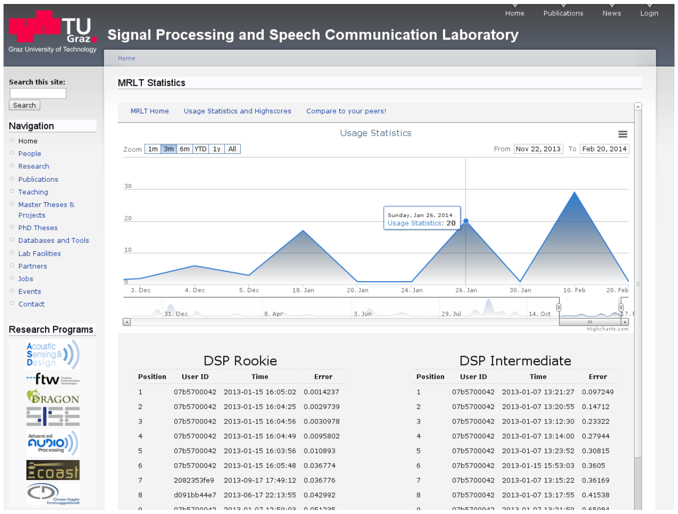

Fig. 2. Screenshot of the MRLG webpage (high-scores and usage statistics).

of the magnitude response graph. Eventually, for real-valued filters, every interpolation point is automatically mirrored at the ordinate axis, enforcing the students' understanding that real-valued filters have symmetric magnitude responses. As can be seen in (B) in Fig. 1, two periods of the magnitude response are shown: The students are continuously exposed to the periodicity of the magnitude response of a discrete-time filter.

If a pole/zero chart contains multiple zeros or poles, the magnitude respose can exhibit multiple minima or maxima, possibly with different values. In general, a minimum (maximum) is more pronounced, i.e., has a lower (higher) value, the smaller the distance is between the zero (pole) and the unit circle. While most students claim to understand this connection, they nevertheless occassionally fail to draw appropriate magnitude responses. The situation is even more complicated if zeros are placed both inside and outside the unit circle. In this case, distance is not measured in an Euclidean sense, but w.r.t. mirroring on the unit circle: A minimum corresponding to a zero z_o outside the unit circle is more pronounced than one corresponding to a zero z_i inside the unit circle if $1/z_o > z_i$. To improve the students' understanding of these concepts, higher difficulty levels feature higher-order filters with multiple poles and zeros, allpasses, and non-minimum phase filters having zeros both inside and outside the unit circle.

The MRLG was developed in the framework of a bachelor thesis during 2012 and was first released in January 2013. A second bachelor thesis added features to the game and developed the webpage, including statistical evaluations. While we encouraged students to use the MRLG for exam preparations already during the summer term 2013, the game was first officially introduced in the problem classes of summer term 2014. Subsequently, the present study was conducted within the framework of two bachelor theses. Currently, an online version of the game is being developed by yet another bachelor student.

TABLE II
SCHEDULE FOR THE DSP COURSE AT GRAZ UNIVERSITY OF TECHNOLOGY DURING SUMMER TERM 2014.

3/01	Start of semester
3/17	First problem class
5/19	Problem class about pole/zero plots and magnitude response; introduction of the MRLG; MRLG-related homework assigned (see text)
5/20 - 5/27	First online survey (pretest)
6/6	MRLG-related homework due
6/24 - 6/29	Second online survey (posttest)
6/17 - 7/7	Course evaluation
6/23	Last problem class
7/4	End of semester

IV. SURVEY DESIGN

Our study proposes the following hypothesis: Playing the MRLG has positive impact on the students' performance in drawing a magnitude response based on a pole/zero chart. Specifically, students playing the game often have a lower chance of confusing maxima with minima or positive minima with zeros, have a better understanding about the relative pronunciation of minima/maxima, and place these extremes more accurately on the frequency axis.

To test our hypothesis, we designed two online surveys consisting of both (qualitative) evaluation questions and (quantitative) tasks matching magnitude responses to pole/zero charts. Furthermore, we added additional questions regarding the MRLG to the course evaluation.

A. *Online Surveys*

Two online surveys were designed to test the students ability to match magnitude responses to pole/zero charts and to determine their self-assessmentof this ability. The first of these surveys was conducted immediately after introducing the connection between pole/zero charts and magnitude responses in class, while the second survey was scheduled roughly a month later, during which time the students could play the MRLG (see Table II for the placement of surveys within the term's schedule). While the first survey was essential to determine the prior knowledge of the students, the second survey served to estimate the effect of the MRLG on the students' performance. Since students are naturally expected to improve also without using the MRLG (e.g., because the connection between magnitude responses and pole/zero charts was also the focus of a homework assignment during this time), we asked the students to state the number of played rounds (which can be read off the score chart (H) in Fig. 1). Students could select one out of five categories: 0-10, 10-20, 20-50, 50-100, and >100. Moreover, students should evaluate the tool at the hand of a few yes/no- or Likert-type questions. Table III shows the questions asked during the online surveys. While Q1 and Q2 where asked during both surveys to assess the development of students' self-confidence, Q3 through Q7 were only asked during the second survey.

To test the students' understanding of the connection between magnitude responses and pole/zero charts, each survey consisted of five multiple choice questions: In these, students were presented a pole/zero chart and six magnitude response

TABLE III
QUESTIONS AND POSSIBLE ANSWERS FOR THE ONLINE SURVEY.

	Question	Answer
Q1	Do you understand the relationship between the pole/zero chart of a filter and its magnitude response?	yes/no
Q2	Can you construct the magnitude response of a pole/zero chart qualitatively?	yes/maybe/no
Q3	Do you think the learning tool is useful?	yes/no
Q4	Do you think it was a good idea that the learning tool was used in this course	yes/maybe/no
Q5	Would you like more computer- or web-based learning aids (such as the Magnitude Response Learning Game) in this or other courses	yes/no
Q6	The learning tool was helpful for understanding the topic in this course?	strongly disagree/ disagree/undecided/ agree/strongly agree
Q7	How often did you use the learning tool? How many rounds did you play?	0-10, 10-20, 20-50, 50-100 and >100)

TABLE IV
PENALTIES FOR THE ONLINE SURVEY'S MATCHING TASKS (SEE TEXT AND FIG 3).

Error Type	Penalty
Confused max with min	2 pts
Magnitude response is shifted by π	1.5 to 2 pts
Confused min with zero	0.5 pts
Narrow/wide extremum	0.25 to 1 pts
Relative pronunciation of extrema	0.25 to 0.5 pts
Position of extremum wrong	0.25 pts

graphs. Only one of these six magnitude response graphs corresponded to the pole/zero chart, the other five contained smaller (correct extrema but incorrect pronunciation, etc.) or larger (maxima and minima confused) errors. The student had to choose the magnitude response matching the pole/zero chart and received points depending on the accuracy of their match. In total, two points were available for each question, choosing an erroneous magnitude response led to the penalties described in Table IV (if several errors occurred, the penalties were accumulated to a maximum of two points). Fig. 3 shows one of the questions, together with the assigned points. In a sixth question, the task was reversed: There, students were presented a magnitude response and had to choose one of six pole/zero charts. Again, two points could achieved. To ensure that the difficulty of both online surveys is equal, the same six questions were asked in both surveys. To reduce a possible maturation effect, the true answers were not revealed to the students in either survey.

The surveys where designed, implemented, and automatically graded in TeachCenter (TC, see [18] for a description of an early version of the system), the online learning platform of Graz University of Technology. TC is an interactive platform for communication between students and tutors and is used in many courses at the TU Graz, hence students are assumed to be familiar with the interface. After informing them about the intentions of our study and about the voluntary nature of their participation, students were asked to sign in via their university account in order to match the results of both surveys. The pretest was accessible for eight days, the posttest for

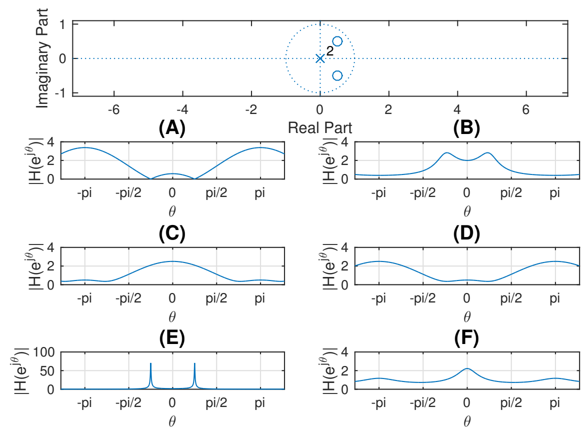

Fig. 3. Example of the online survey's matching task. (D) is the magnitude response corresponding to the pole/zero chart (2 pts). In (A), minimas and zeros are confused (1.5 pts), (B) and (E) have confused maxima and minima (0 pts), (C) has the magnitude response shifted by π (0 pts), and (F) has too wide minima at wrong positions and a wrong relative pronunciation of maxima (0.5 pts).

six days. Once accessed, the student had to complete the survey within 60 minutes. Each survey could be accessed only once. Automatic grading eliminated instrumentation bias. In order to encourage students to participate in the surveys, each completed survey granted them three bonus points for the DSP problem classes (amounting to 3% of the achievable points for this course).

B. Course Evaluation

At Graz University of Technology, courses are evaluated regularly based on a schedule published by the study deans' offices. In addition, lecturers can permit course evaluation on a voluntary basis. In both cases, the evaluation is conducted online: each student registered for this course can access the questionary once, within a time window of at least two weeks (cf. Table II). Course evaluation is not mandatory for students, hence return rates below 20% are standard. The questionary consists of a standardized part querying students' attendance, subjective difficulty ratings, and quality of contents, course material, and teaching. Moreover, students can express positive and negative feedback in textboxes. Most questions can be answered via 5-point/6-point Likert-type scales.

Additionally, lecturers can extend the questionary by customized questions, a feature we have been using during the last years. We used 4-point Likert-type scales to query specific aspects of teaching quality (readability of the blackboard, speech intelligibility). To get feedback on students' understanding, we used 5-point Likert-type scales to determine which topic areas (e.g., convolution, discrete-time Fourier transform, sampling and reconstruction, etc.) were well understood. At the hand of another set of 4-point Likert-type scales and a textbox we queried the students' satisfaction with the MRLG (see Table VII and Section V-C). In particular, we wanted to know whether the students used the tool, whether they found it worthwhile, whether they wish to have more such tools for this course and whether the MRLG motivated them to learn more about DSP.

V. Survey Results

Of all 324 students registered with the course during the summer term 2014, 91 completed the first online survey and 122 the second, of which 61 completed both surveys. Of these 61, twelve were female. All following statistical tests are based on these 61 students. Furhermore, of all 324 students, 73 filled out the end-of-term course evaluation. Since the course evaluation is anonymous, it was not possible to determine the overlap between these two samples.

A. Online Survey Results – Matching Problems

The goal of this analysis was to test hypothesis H1, i.e., whether using the MRLG improves students' performance in related tasks. During the pretest, students on average achieved 5.9 points (standard deviation 3.2), while on the posttest the average score was 7.9 points (standard deviation 3.4, cf. Fig. 4). To determine whether the difference between the data collected in the first and second online survey is statistically significant, a two-sample t-test was performed. With a sample size of $n = 61$ and a p-value of $6.214e-05$ we can answer this question affirmatively and model the difference statistically. This and all following statistical analyses were performed with GRETL[3], an open-source software package for econometric analysis.

A linear regression model is used to characterize how the number of played rounds and the points achieved in the pretest influence the performance during the posttest. The number of played rounds were available via class labels, C_1 through C_5, corresponding to the classes displayed in Table III: Class 1 with label C_1 consists of all players playing less than ten rounds, class 2 with label C_2 contains players playing between ten and 20 rounds, C_3 for 20 to 50, C_4 for 50 to 100, and C_5 for more than 100 rounds. If the data sample belongs to a class x the value of C_x is set to one and the values of all other parameters C_y, $y \neq x$, are set to zero. C_1 appeared 13 times, C_2 and C_3 18 times each, and C_4 and C_5 appeared 6 times each, guaranteeing a large enough variance for the class labels to ensure valid statistics. Fig. 4 shows the average numbers of points achieved for each class, both during the pre- and the posttest. As it can be seen, students who played less than ten rounds did not improve at all, while the improvement increases with increasing number of played rounds.

In order to remove possible bias due to differences in student motivation or overall performance, both the points achieved in the pretest and the total number of points achieved during the problem class via submitting homeworks is considered in the model as well[4].

TABLE V
Coefficients of the linear regression model and their p-values.

Parameter	Coefficient	p-Value
C_2	1.72451	0.0826
C_3	2.41764	0.0120
C_4	2.84017	0.0300
C_5	3.66538	0.0068
$pretest$	0.285693	0.0186
$homework$	0.0626376	2.29e-05

$$posttest = a_1C_2 + a_2C_3 + a_3C_4 + a_4C_5 + a_5pretest + a_6homework \quad (1)$$

To avoid problems with multicollinearity and dummy variables (this is also referred as dummy variable trap) the parameter of the first class C_1 is not explicit in the model (however, all class parameters set to zero indirectly indicate C_1). $pretest$ and $posttest$ represent the number of points achieved in the first and second online survey, respectively, while $homework$ represents the total number of points achieved for solving homework assignments.

The linear regression coefficients a_i were estimated using ordinary least squares (OLS). To ensure that the confidence values derived for the regression parameters are meaningful, heteroskedasticity has to be excluded: We performed a White test [19, page 269-270], and a p-value of 0.225459 does not reject the null hypothesis of homoskedasticity. Our results are thus unbiased and descriptive. Table V shows the coefficents of the linear regression model together with their p-values. Note that the significance level of most of the coefficients is below 0.05, with exception of C_2, which is below 0.1.

The coefficients a_i in Table V indicate how many additional points are achieved in the second survey when increasing the value of the corresponding parameter by one. All a_i are positive, indicating a positive correlation between the performance during the posttest and the respective parameter. However, this positive correlation is stronger for class labels corresponding to a larger number of played rounds: While using the MRLG between ten and 20 times leads to additional 1.72 points as compared to students never playing the game, using the MRLG between 50 and 100 times already yields an improvement of 2.84 points[5]. Considering that in each survey 12 points were achievable, the improvement caused by playing the MRLG is substantial. The analysis also shows that the performance in the first survey has only slight effects on the performance during the second survey (cf. Fig. 4). With

[3] http://gretl.sourceforge.net/

[4] Note that one task of the homework considered drawing a magnitude response function based on a given pole/zero chart. This leads to a correlation between the posttest score, the total number of achieved points, and the number of played rounds. Since this correlation is known to be problematic when determining the regression coefficents via ordinary least squares, $homework$ in (1) is corrected according to the points achieved on this subtask of the homework assignment.

[5] The improvement indicated in Fig. 4 does not immediately reflect these values: There, students in class 2 on average improved by two points, while students in class 4 improved by 2.75 points, on average. The reason for this discrepance is that Fig. 4 does neither consider the points achieved for submitting homeworks, nor the performance during the pretest.

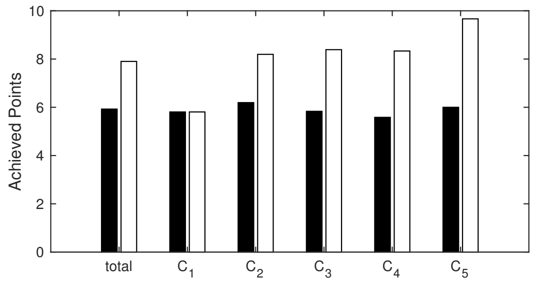

Fig. 4. Average student scores during the pretest (black) and posttest (white). It can be seen that while the average scores in the pretest are largely independent from the class labels, the performance during the posttest improves with increasing number of played rounds.

the parameter $homework$, the overall learning performance of a student is taken into account. Students with high learning performance and motivation are more likely to acquire more knowledge, hence perform better in both homeworks and online surveys. As the statistics show, one additional point on the homework assignments increases performance of the second test by 0.06 points. Since this improvement is small in comparison to the improvement achieved by playing the MRLG, we conclude that H1 is correct and that playing the MRLG has positive effect on the students' understanding of the connection between the pole/zero chart of a filter and its magnitude response.

B. Online Survey Results – Evaluation Questions

We now come to the results of the questions Q1-Q6 asked during the first and/or second online survey (see Table III). Questions Q1 and Q2 queried the students' subjective evaluation of their ability to understand the relationship between pole/zero charts and magnitude responses and to draw the latter based on the former, respectively. As expected, over time students became more confident of their capabilities (see Table VI).

As Table VI shows (Q3-Q5), the students are clearly in favor of the MRLG and think it a good idea to use such tools in this and other classes. The answers to Q6 show that while a large part of the students is undecided whether the MRLG helps in understanding this course's topics, an equally large part of students is inclinded to think so. Hence, while Q3 ("Do you think the learning tool is useful?") confirms that students believe that the MRLG is beneficial for their performance in drawing magnitude responses, Q6 shows that the game's effect on the students' performance in other DSP-related topics is limited.

C. Course Evaluation Results

The course evaluation, in which 73 of all 324 students participated, revealed that the contents of the course were experienced as appropriate (36.6%) or difficult (63.4%), and that the workload was moderate (26.8%) or high (60.6%), compared to other courses at our university. Nevertheless, the majority (>60%) of students agreed that the course material was delivered in an appropriate way, that they learn a lot in this

TABLE VI
RESULTS OF THE EVALUATION PART OF THE ONLINE SURVEY.

Question	**Yes** Strongly Agree	Agree	**Maybe** Undecided	Disagree	**No** Strongly Disagree
Q1 (first test)	59,02%	-	-	-	40,98%
Q1 (second test)	78,33%	-	-	-	21,67%
Q2 (first test)	13,11%	-	63,93%	-	22,95%
Q2 (second test)	31,15%	-	65,57%	-	3,28%
Q3	98,33%	-	-	-	1,67%
Q4	95,08%	-	4,92%	-	0,00%
Q5	93,44%	-	-	-	6,56%
Q6	4,92%	34,43%	34,43%	24,59%	1,64%

TABLE VII
MRLG-SPECIFIC COURSE EVALUATION RESULTS. μ IS THE MEAN VALUE, σ THE STANDARD DEVIATION.

Question	**Agree (3)**	**Somewhat agree (2)**	**Somewhat disagree (1)**	**Disagree (0)**	μ	σ
I used the learning tool	53.5%	16.9%	12.7%	16.9%	2.07	1.15
The tool motivated me to learn more about DSP	14.1%	18.8%	45.3%	21.9%	1.25	0.95
Introducing the tool is a good idea	58.7%	25.4%	9.5%	6.4%	2.37	0.9
I would prefer more such tools for this course	59%	31.2%	4.9%	4.9%	2.44	0.8

course, and that they are in general satisfied with the course quality. The convolution of signals and the z-transform were among the topics that were easiest to understand, while the most problematic ones were multi-rate systems, quantization effects, and filter design (these topics were taught at the end of the semester). We also asked students to rate their experience with the MRLG, hoping to confirm the results from our TC tests. Please note that, since the course evaluation is anonymous, there is no way to identify the overlap between the 73 students evaluating the course and the 61 participants of the TC tests. The results (summarized in Table VII) reflect the students' being in favor of the MRLG, although they admit that the tool did not influence their motivation to learn DSP.

Students had the option to add comments during the course evaluation, an option which 22 students made use of. Of these, four expressed their positive attitude toward the MRLG ("visual components help understanding", "playful way of learning complex mathematical circumstances", etc.), five requested a detailed tutorial explaining the MRLG, and and six students mentioned that they could not access the MRLG because they lacked a MATLAB license. Currently, this last issue is being addressed via working towards an online implementation of the MRLG. The full course evaluation results are available upon request.

D. Threats to Validity and Outlook

Both during design and conduction of the quantitative part of our study, we tried to limit possible harms to internal or external validity. A confounding factor we were not able to investigate, for example, is the willingness of a student to participate actively. On the one hand, students who fill out a voluntary online survey are clearly more willing to participate actively than students who do not. On the other hand, the willingness to participate may be positively correlated to the student's performance in class, hence we might be faced with an unintended selection bias. In order to reduce this bias as much as possible, we awarded participation in each survey by bonus points. Moreover, student performance in class (an expected confounding factor), was considered in the model. Nevertheless, our reported results may be inaccurate in the *rate* of improvement caused by using the MRLG: Students with a higher motivation may not only play the game more often, but may also benefit more from playing a single round than other students would. We believe, however, that this does not threat the conclusion that our hypothesis H1 is correct.

The maturation effect is a common threat if pre- and posttests are similar. In our case, in which pretests and posttests were even identical, we tried to eliminate this effect by not measuring the performance change between these tests, but by measuring the performance change *as a function of the number of played rounds*. Moreover, since the correct results of neither the pretest nor the posttest were revealed to the students, we claim that the maturation effect would have been small anyways. Instrumentation bias was excluded by computing test scores automatically based on a predefined grading scheme.

Concerning the generalizability of our results, the following facts have to be taken into account: Students of this course had no or very little prior knowledge about the connection between the pole/zero chart of a filter and its magnitude response, hence results may look different when prior knowledge is available. Moreover, the improvement caused by playing the MRLG may depend on the way how this connection is taught at Graz University of Technology ([1] gives a brief account on that). Finally, other factors affecting students performance, e.g., goal orientations [20], have not been considered. Hence, we are cautious with generalizing our quantitative results to students of other universities. We believe, however, that a qualitative trend still applies.

Finally, the qualitative part of our study (course evaluation, MRLG evaluation during the online survey) is subject to severe threats to validity, mostly confounding. It appeared not to be sensible to weight the responses to Q1-Q6 (see Table III) by the number of played rounds, hence the positive feedback may be in part due to students having a higher willingness to participate. The same conclusion applies to the results of the course evaluation. Taking this into account together with the threats to validity of the quantitative part, we regard this study as a first exploration of the effects of MRLG on students' performance. Future studies shall investigate whether MRLG can be used effectively in exam preparation, the influence of MRLG on students' confidence regarding related tasks, and whether or not playing the MRLG increases students being in favor of online-or computer-based learning tools.

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