THE THREE "R"S: REAL STUDENTS IN REAL TIME DOING REAL WORK LEARNING CALCULUS

Steven M. Hetzler[1]
Robert M. Tardiff[1]

Salisbury University
Department of Mathematics and Computer Science
Salisbury, Maryland, USA
smhetzler@salisbury.edu
rmtardiff@salisbury.edu

ABSTRACT

In this paper, we describe sonifications designed to teach calculus of a single real variable, and report on how students in a typical class perform using these sonifications. We draw three conclusions from this evidence. First, even relatively weak students in an introductory calculus course can, with little specialized instruction, learn to interpret such sonifications quickly. Next, sonifications designed to engage students and containing sufficient audio cues have the potential to improve learning in calculus. Last, such sonifications can easily be integrated into a typical calculus class, for typical calculus students.

[Keywords: Auditory Graphs, Sonification Applications, Teaching with Sonification]

1. INTRODUCTION

In learning mathematics, some students more readily learn in a visual mode (graphical) than in a verbal mode (text), so topics presented to such students visually are easier for them to learn than if presented verbally [1]. By the same token other students learn more readily in a verbal mode than graphical. Moreover, translating a mathematical situation described in one mode to another not only helps students learn to operate in both modes, but also often leads to a deeper understanding of the mathematical concept. So, the focus of our research is to determine if teaching students mathematics using sonifications provides yet another effective mode for teaching, learning, and discovering mathematical concepts. This builds on work done in [2][3][4][5].

The use of various modes for representing mathematical concepts is a standard approach to teaching calculus. The usual setting is to present a topic in four different ways: numerically, graphically, symbolically, and verbally, and this approach is often called the Rule of Four [1][6][7]. Students are expected to be able to describe and develop a mathematical concept using any one of the four modes and to readily translate from one mode to another.

We follow this Rule of Four approach in using sonification in calculus instruction and view sonification as a fifth mode which we call the Rule of Five [8]. Students see sonification as yet another mode to describe, analyze, and learn mathematics. Just as in the Rule of Four, we expect students to readily move among the modes. Before this idea is widely implemented, three questions would need to be answered. The first question is whether sonification can be integrated into calculus instruction without an inordinate investment of technology and faculty time. The second is whether students, especially those that need the most help learning calculus, can interpret sonifications well enough to be able to use them as a learning tool. Finally, the third is whether sonification has potential to improve student learning in calculus. To the first two questions, we have fairly solid evidence that the answer is yes, and to the third question, we have preliminary evidence that the answer is yes as well.

2. METHODOLOGY

Sonification activities are integrated into a standard calculus course, populated primarily by business majors. While as many as ten percent of the students are non-business majors, none are mathematics, statistics, or computer science majors. Each section has approximately thirty students and meets for three fifty-minute sessions per week for fourteen weeks. Each sonification activity requires one of the fifty minute sessions to complete. For a sonification activity the class meets in a networked computer laboratory equipped with an instructor's computer station with projection capability and thirty standard Windows-based PC's with headphones. All other sessions are held in a standard classroom with an instructor's computer station, including projection and sound capability which the instructor can use to demonstrate concepts in any of the modes including sonification. (None of the students have used laptops in the classroom.)

The first author taught two sections in Fall 2005 and two in Fall 2006. Students were not selected to participate in this study; these students had simply registered for one of fifteen available sections of the course. In 2005, the sonification training activity was done at mid semester, and we note that by mid semester several students had withdrawn from the course, primarily because they were not passing. In 2006, the training activity was

completed within the first two weeks of the semester. As a result, more students completed the activity, but some of these students would later withdraw from the course.

2.1. Sonifications

In a calculus course the focus is on continuous functions of one variable defined on a continuous domain or interval, so our sonifications are auditory graphs representing continuous functions of one variable defined on an interval, [a, b]. The x-values are mapped to time, and the y-values, logarithmically, to frequencies between 220 Hz and 660 Hz. Since functions typically studied in calculus vary continuously, our sonifications vary frequency continuously, rather than changing it in steps (see [9]). We then modified this basic design to create more pleasant sonifications and allow students to more easily locate the sound source and to extract mathematical information from the sonifications.

The first modification is to map y to the root note of a major chord, and play that chord, rather than a single frequency. A major chord sounds more pleasant than a single frequency, and its multiple frequencies allow for easier location of the sound source ([10] and [11]).

The next modification addresses the importance of being able to distinguish easily between positive and negative values of a function. This is done by adding a small amount of white noise or hiss to the chord when it represents a negative number, similar to the work in [12]. Previously, minor chords had represented negative values, but students did not seem to be able to detect the change between major and minor chords quickly and reliably when they had several other things to track ([9]).

The third modification helps students identify when a function is zero, but does not change sign. A small ping is added to the waveform whenever the value of the function is very near zero.

The last modification is a regular pulse added to the wave form ([13]). By counting the number of pulses or the intervals between pulses, students can keep track of location on the horizontal scale. This cue is related to ideas found in [14] and [15].

2.2. Tools

Our sonification activities are supported by commonly available and familiar software. This is important because the goal of our project is to improve student learning in a standard calculus course for typical students. The less time spent teaching a software package the more time available to work with students on the mathematics.

To give students the basics on how to interpret sonifications, we use a web browser to present a collection of sonifications and graphs for students to analyze and interpret. Students are asked a series of multiple choice questions based on the sonifications and graphs. Instant feedback is provided to students as they respond to each question. And to give students the ability to construct sonifications of function we created a library of subroutines for Microsoft Excel that allows a student to input a function and immediately produce its sonification. More information on these tools can be found in [9].

2.3. Student Activities

In this paper we report on students' performance using these tools to complete two of five activities that we are integrating into this course. The first activity, and the first on which we are reporting, is a Training Activity, where students learn to interpret our sonifications. In the second activity, students use sonifications to learn to recognize and interpret some important qualitative properties of functions: sign, direction, and curvature. In the third activity, students use sonifications to learn to recognize and find limits of functions. The second activity we are reporting on is the fourth activity, in which students learn to relate qualitative properties of the derivative of a function to qualitative properties of the function itself. The final activity is a capstone in which students learn to locate extreme values of a function using its derivative.

3. RESULTS

3.1. The Training Activity

The training activity is where students use our web based tool to learn the basics on how to interpret sonifications. Sonifications in the training activity contain all cues except the ping for zero, which is only used in our calculus activities. The activity has six sections; the first two sections have ten items each, and the other four have five items each. Each item is multiple choice, with four choices, only one of which is correct. Students recorded their *first* response to each item in individual spreadsheets. When students select an answer, they receive immediate feedback indicating whether they were right or wrong and often a hint on how to go back and identify the correct answer.

The six sections are:

1. Estimate the numeric value of a sonification, on a whole number scale between 0 and 10;
2. Estimate the numeric value of a sonification, on a whole number scale between -5 and 5;
3. Associating auditory graphs with visual graphs
   a. Given an auditory graph, identify the corresponding visual graph;
   b. Given a visual graph, identify the corresponding auditory graph;
4. Given an auditory graph of a function, identify the subinterval in which the function's maximum value is attained; and
5. Given an auditory graph of a function, identify the subinterval in which it has a zero.

Notice that Sections 1 and 2 are similar to the work in [16]. The reader might wonder why there is a section 3a. and a section 3b. To save time in both Fall 2005 and Fall 2006 students in one of the sections of the course completed 3a., but not 3b., and students in the other section completed 3b. but not 3a.

3.1.1. *Overall Analysis of 2005 and 2006 performance*

To see how well students perform overall on the tasks in this activity and to see whether student performance can be replicated

from year to year, we compared data from 2005 [9] to data from 2006. As noted in [9], the results for Sections 4 and 5 were flawed in 2005, because of a programming error. So, while we analyzed all of the responses from 2006, any comparison we make of performance between 2005 and 2006 relies only on data from the first three sections.

Overall the students in 2006 and 2005 performed well on these first three sections and moreover performed, in general, equally well. Table 1 tallies the number of students performing at various levels on these three sections. Using a chi-squared test, we find no significant difference ($p \sim 0.84$) between the performance in 2005 and performance in 2006.

Score	2005	2006	Total
0 – 30%	0	0	**0**
31 – 60%	10	15	**25**
61 – 80%	22	26	**48**
81 – 100%	12	13	**25**
Total	**44**	**54**	**98**

Table 1. 2006 results consistent with 2005 results

Since the data from 2005 and 2006 arise from approximately the same distribution, it is reasonable to combine the two data sets to study whether students can quickly and easily learn to perform these tasks. Approximately three fourths of students answered 60% or more of the questions correctly, and none of the students answered fewer than 30% correctly. It is clear students are not randomly guessing, since a randomly guessing student could be expected to answer only 25% of the questions correctly. So there is evidence students can learn to interpret sonifications such as those found in Sections 1 through 3 quickly and reliably. And, as will be seen later in this paper, the conclusion that students learn to perform these tasks readily is also supported by 2006 performance on Sections 4 and 5.

3.1.2. *Analysis of Sections 1 and 2: Estimating Value*

Figure 1 and Figure 2 indicate that overall, students did well on Sections 1 and 2, supporting the results of [16]. It also appears that there may be some evidence that students performed differently on estimating value in 2005 than in 2006. Indeed, a chi-squared test on Section 1 data shows a possibly significant ($p \sim 0.07$) result; however, a chi-squared test on Section 2 indicates no significant difference ($p \sim 0.59$) between the two years. One possible explanation for any difference is that there might be a relationship between performance on these tasks and completion of the course. As mentioned earlier, a higher proportion of students completing the activity in 2006 did not complete the course. The inclusion of these students in the 2006 data might skew the results toward slightly poorer performance.
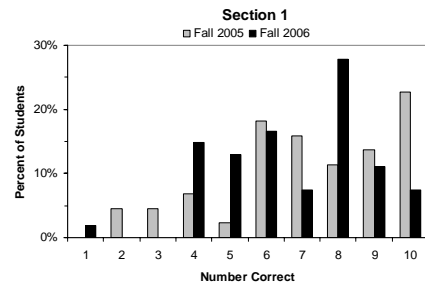

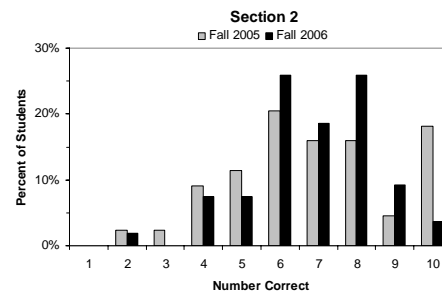Figure 1. *Results for Section 1 by year.*

Figure 2. *Results for Section 2 by year.*

In the questions that included negative values in the scale, we found almost no difference in the distribution of scores between 2005 and 2006. Recall, students in 2005 had a minor chord as a cue for negative values while students in 2006 had hiss or white noise as the cue. Because students performed generally well on this section in both 2005 and 2006 (more than 90% of students in either year correctly identified negative values as negative and non-negative values as non-negative), we are not able, in this subset of the data, to see any improvement in performance due to new cue (the white noise) for negative values. However, there is evidence in other sections of this activity that it improves ability to interpret auditory graphs.

3.1.3. *Analysis of Sections 3a. and 3b.: Visual and Auditory Graphs*

In both Fall 2005 and Fall 2006 all students in one section of the course completed Section 3a. and the other section completed Section 3b. In Section 3a. students are presented with a sonification and are asked to select a graph that corresponds to it from among four choices. The students who completed this activity will be called the *Selected Graph* students. In Section 3b., students are presented with a graph and are asked to select a sonification that corresponds to it, from among four choices. These students will be referred to as the *Selected Sound* students.

We find no significant difference between the performance of 2005 *Selected Graph* students and 2006 *Selected Graph* students ($p \approx 0.7$), nor between the performance of 2005 *Selected Sound* students and 2006 *Selected Sound* students ($p \approx 0.4$). In fact, the students performed well on both of these activities both years; three-fifths of *Selected Graph* students answered at least four of five exercises correctly and four-fifths of *Selected Sound* students performed that well.

Originally, Sections 3a. and 3b. were only separated from each other to conserve time; with only fifty minutes for students to complete all of these activities, we felt it unnecessary for all students to complete both of these sections. We expected that we'd investigate differences in performance on Sections 3a. and 3a., but had no prior assumptions about which type of exercise would be better training, or on which type students would perform better.

Even in 2005, there didn't seem to be significant differences ($p > 0.60$) in performance between *Selected Graph* and *Selected Sound* students on Section *3*, but in 2006, there is some evidence ($p \approx 0.08$) of better performance in the *Selected Sound* group than in the *Selected Graph* group.

Two exercises deserve comment for the evidence that they might provide that the hiss cue for negative values is easier for students to interpret than a minor chord. In the third exercise of the *Selected Graph* set (Exercise 23), the sound increases and has its x-intercept precisely in the middle of the interval. All of the graphs are increasing, and only the second and fourth graph choices have the x-intercept in the right location (the second graph is the correct choice; see Figure 3). In 2005, 54% of students chose Graph 2 or Graph 4, thus correctly identifying the location of the x-intercept, while in 2006, 72% of students correctly located the x-intercept. This is the best evidence so far ($p = 0.1$) that the hiss cue is better for students. In both years, Graph 2 was the overwhelming choice of those students who correctly located the x-intercept.
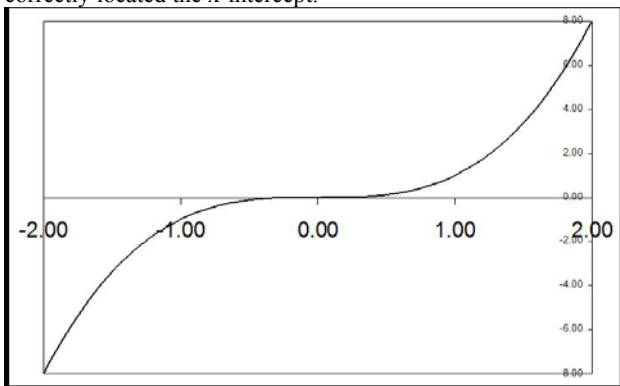

Figure 3. *The correct response in Exercise 23.*

The other exercise to note is the second in the *Selected Sound* set (Exercise 27). On this exercise, the graph increases throughout the interval, and has an x-intercept in the middle of the interval. Of the sounds, only one (Sound number 4) was increasing with the x-intercept precisely in the middle, i.e.: the sound hissed until the very middle and then stopped. Of the incorrect sound choices, one (Sound number 2) increased and decreased, and very few chose it in either 2005 or 2006. While Sounds 1 and 3 increased as the graph did, the location of their x-intercepts was too small and too big respectively. In 2005, there was more confusion ($p = 0.003$) among Sounds 1, 3, and 4.
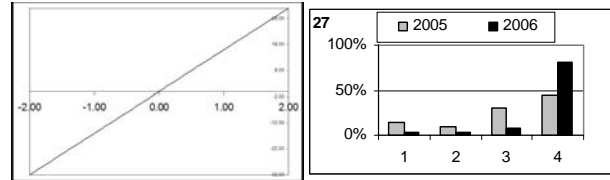

Figure 4. *Graph given in Exercise 27 and student performance.*

Together, these two exercises provide a look at students' ability to interpret the cues for negative values. While some students are in the *Select Sonification* group, and others are in the *Select Graph* group, Exercises 23 and 27 together allow a look at all students.

These two exercises also illustrate an important point about this Training Activity. With the new cue, the location of an intercept is information gathered at a glance, rather than by careful listening. Distinguishing major chords from minor chords can also be information gathered at a glance, but only with proper ear training. Since the students are limited to fifty minutes to complete this activity, and since for many students this is the first experience in a computer lab for the course, if not for their University experience, and since they have thirty-five questions to answer, information at a glance is very important information.

3.1.4. Analysis of Sections 4 and 5: Locating Extremes and Intercepts

We will not analyze the data for Sections 4 and 5 for 2005. As we reported in [9], the feedback to students indicating whether or not they had selected the correct answer was flawed.

The exercises in Sections 4 and 5 ask students to listen to a sonification of a function, particularly for the location of a maximum (Section 4) or an x-intercept (Section 5). Recall the sonifications contain a regular pulse to help students keep track of position on the horizontal axis (time).

In Section 4, students were presented with a sonification of a function and asked to identify in which of four subintervals the maximum value of the function occurred. There were no visual cues; i.e., no graphs as in the previous sections. The only information the student had was the sonification.

Overall, students did well on this task. Fifty-eight percent of the students answered three or more of the five questions correctly. If students were guessing, the probability that a student gets three or more correct is 0.10. So, one would expect that about 10% of the students would get 3 or more correct instead of the observed 30. Thus the students did significantly better (p essentially 0) than one would expect if they were guessing.

However there were significant differences in the performance of students who were in the *Selected Sound* group over students who were in the *Selected Graph* group ($p < .02$). Looking at Figure 5, students who were in the *Selected Sound* group did much better overall than those in the *Selected Graph* group.
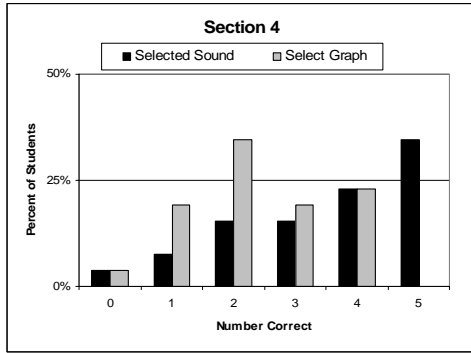
Figure 5. *Difference in performance: locating maximum.*

Looking at an item analysis of Section 4 (see Figure 6), we can see that the *Selected Sound* group outperformed the *Selected Graph* group on 4 of the five items ($p \sim .19$), which is not significant, but item 35 is of particular interest and bears further explanation.
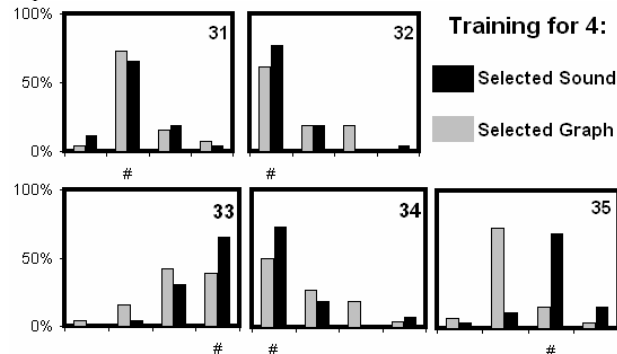

Figure 6. *Item analysis of Section 4.*

The function used in item 35 attained its maximum value in the third interval. The value of the function at the left endpoint of the third interval is less than the value of the function at its maximum, but not very much less, so the pitch of root note at the left endpoint of the third interval is less than the pitch of the root note at the maximum, but, again, not that much less. Recall that at the left endpoint of the third interval the volume of the sonification was briefly increased from the normal volume. Note that the *Selected Graph* group had heard five sonifications with pulsing prior to starting Section 4 while those in the *Selected Sound* group had heard twenty. We speculate that the brief increase in volume may have led the *Selected Graph* students, who didn't have as much experience with pulsing to confused the brief increase in volume with increase in pitch.

In Section 5, students were presented with a sonification of a function f and asked to identify the subinterval where the graph crossed the x-axis; i.e. where the function changes sign. As in Section 4 there were no visual cues. The only information the student had was the sonification itself which included the volume increases and "hiss" for negative numbers. Overall, students did well on this task, with 30 out of 52 answering three or more correctly, again implying students are doing much better than just guessing.
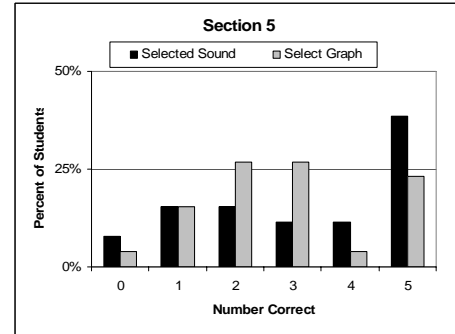

Figure 7. *Difference in performance: locating intercept.*

Contrary to the results of Section 4, in Section 5 the overall performance of students who were in the *Selected Sound* group was not significantly different from that of students who were in the *Selected Graph* (p $\sim$ .53). This is also borne out in an item analysis of Section 5; see Figure 8.
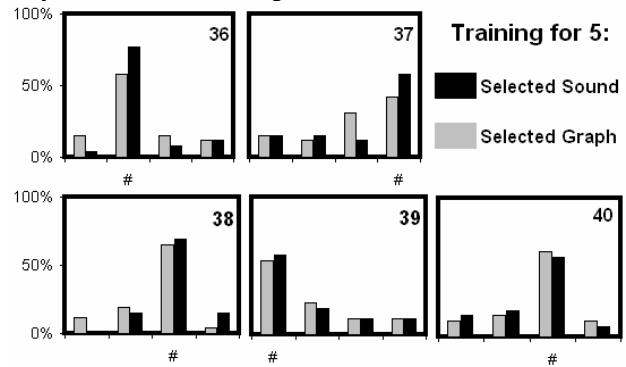

Figure 8. *Item analysis of Section 5.*

To conclude the analysis of Sections 4 and 5 we again note that performance differences the Section 4 between the *Selected Sound* group the *Selected Graph* group may be attributable to experience. Students in the *Selected Graph* group had to analyze five function sonifications and twenty graphs, while those in the *Selected Sound* group had to analyze twenty sonifications and five graphs. Since graphs are very familiar to calculus students and sonifications are not, one should not be surprised that more practice with sonifications in the context of graphs would lead to better performance with sonifications only.

This premise may be reinforced by the data in Section 5 as well. Both groups acquired experience and reinforcement in analyzing and extracting information from a sonification only. That experience could explain why both groups did about the same on Section 5.

The results of the training activities indicate that calculus students can learn how to interpret pitch/time sonifications quickly and accurately; i.e. in the space of one fifty minute laboratory students can learn to interpret elementary sonifications.

3.2. The Calculus Activity

The sonification activity we are reporting on is designed to help students understand calculus through sonification. The primary learning objective is that students learn how to recognize and

interpret two qualitative properties of functions using all five modes of representation: numerical, graphical, symbolic, verbal, and auditorial. The two essential properties students are identifying are *direction*, whether the function increases or decreases, and *concavity*, whether the graph is bending up or down. We introduce these properties with illustrative examples, and then ask the students to demonstrate their ability to recognize and interpret the properties in all five modes.

For instance, after the concept of direction is introduced to students, they are told to consider the graph presented in Figure 9, a table of data (part of which is replicated in Table 2), and the sonification, all of which represent the function $f(x) = x^2$, for $-4 \leq x \leq 0$.
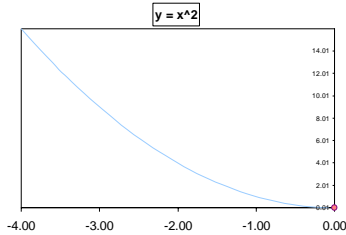

Figure 9

x	f(x)
−4	16
−3.9	15.21
−3.8	14.44
−3.7	13.69
−3.6	12.96

Table 2

The students then respond to four questions:
  a. Is f increasing or decreasing on this domain? *[Correct response: Decreasing]*
  b. How do you see this in the graph? *[Correct response: The graph slopes down from left to right.]*
  c. How do you see this in the table? *[Correct response: As the x-values increase, the y-values decrease.]*
  d. How do you hear this in the auditory graph? *[Correct response: As the sound plays, the pitch gets lower.]*

On this question 87% of the students correctly identified the function as decreasing. Of those, 90% correctly identified how they heard this in the auditory graph while only 70% could adequately describe how they saw it in the graph or saw it in the table. So, preliminary evidence indicates students may have an easier time describing what decreasing means in terms of an auditory graph as opposed to a table or visual graph. Moreover, 25% of these students described the auditory graph correctly but not the visual graph.

After we demonstrate the notion of concavity with an example, students are faced with a task similar to the first outlined above. Students are told to consider the graph presented in Figure 10, the data in Table 3, and the sonification, all of which represent the function $f(x) = x^2$, for $0 \leq x \leq 4$.
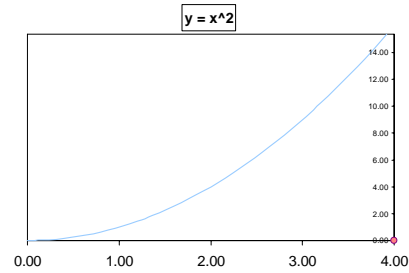

Figure 10

x	f(x)
0	0
0.1	0.01
0.2	0.04
0.3	0.09
0.4	0.16

Table 3

Students then respond to four questions:
  a. Is f concave up or concave down on this domain? *[Correct response: Concave up.]*
  b. How do you see this in the graph? *[Correct response: The graph is increasing throughout, and is steeper on the right side than on the left, or the graph bends up.]*
  c. How do you see this in the table? *[Correct response: The differences in the y values in the table increase as x increases.]*
  d. How do you hear this in the auditory graph? *[Correct response: The pitch increases more quickly as time passes.]*

Concavity is a difficult concept for calculus students to write about in general; they often confuse it with direction. While the data collected from our students bears this observation out, it also suggests that an auditory graph may be more effective than a table of numbers in helping students understand concavity, that it might be as effective as a visual graph, and that the combination of an auditory graph and a visual graph maybe more effective than either alone. Ninety-six percent of the students correctly described f as concave up on this domain. Of those that did, only 17% were able to adequately describe how they saw this from the table, 52% were able to describe what concave up meant graphically, and 48% were able to do so using the auditory graph. Moreover, 61% were able to describe concavity using either a visual or auditory graph or both.

Next, students are asked to address the same questions as in the first example, but with a new function: $f(x) = 3 - x^2$, for $0 \leq x \leq 4$. Here, 87% correctly identify the function as decreasing. All of these students correctly identify the graph features that support their response, while 80% do so with the table and 85% with the auditory graph. These results are an improvement over the first example for the graph and the table, but a slight drop in performance for the auditory graph. Interestingly, even though the students weren't asked about the sign of the function, thirty percent mentioned the white noise present in the sound, indicating the intervals where the function values are negative.

Then, for this same function and domain, students were asked to address issues of concavity. The students were expected to

identify the function as concave down from its graph by noting that its slope decreases or that it bends down, from the table by noting that differences in y values get smaller as x increases, and from the auditory graph by noting the pitch decreases at an increasing rate. There was a noticeable decrease in performance as compared to the second example. Only 46% of the students could interpret concavity using the graph, 13% using the table, and 21% using the auditory graph. The most common error in each category was to confuse decreasing with concave down.

Finally, the students were asked qualitative questions concerning an arbitrary, hypothetical function that was both increasing and concave down. Describing increasing, 62% of the students had acceptable answers for a visual graph, 52% for a table, and 57% for an auditory graph. Describing concave down, 52% were correct for a graph, 33% for a table, and 38% for an auditory graph.

In conclusion this Calculus activity indicates that sonification offers some potential for students learning calculus. The results with concavity were disappointing for all modes; however, it is well known that concavity is a difficult concept for students in any mode.

4. CONCLUSIONS

In closing we see there is evidence that students quickly learn to interpret the mathematics represented by sonifications designed with cues to bring out or emphasize mathematical properties. Our experience with both the training activity and the calculus activity shows that sonifications can be used with typical students with typical computers in a typical course. No special equipment or an extravagant use of time is required to get students actively involved in interpreting and creating sonifications. It also shows that students can easily learn to interpret sonifications with contextual cues, and that sonifications are potentially useful learning tools in calculus. Moreover, students are engaged by the activities, which is one of the purposes of the Rule of Four or more precisely the Rule of Five approach. For instance, the authors observed that the use of sonification in conjunction with other representations tended to focus the students' attention. Thus, the use of sonification resulted in the standard tools for teaching calculus (formula's, tables, and in particular graphs) becoming more effective learning instruments.

A complete study of sonification's potential as a mathematics learning tool requires the involvement of many more mathematics instructors. These instructors need to be introduced to sonification and to tools for producing a wide range of sonifications in a classroom setting.

5. REFERENCES

[1] H. Gardner, *The Unschooled Mind: How Children Think and How Schools Should Teach.* New York: Perseus Books, L.L.C. 1993.

[2] T. L. Bonebright, M. A. Nees, T. T. Connerly, and G. R. McCain, "Testing the Effectiveness of Sonified Graphs for Education: A Programmatic Research Project," in *Proc. Seventh Int. Conf. on Aud. Disp. (ICAD)*, Espoo, Finland, July 2001.

[3] J. H. Flowers, D. C. Buhman, and K. D. Turnage, "Data Sonification from the Desktop: Should Sound be part of Standard Data Analysis Software?" in *Proc. Third Int. Conf. on Auditory Display (ICAD)*, Palo Alto, CA, U.S.A, November 1996.

[4] S. C. Peres and D. M. Lane, "Sonification of Statistical Graphs," in *Proc. Ninth Int. Conf. on Aud. Disp. (ICAD)*, Boston, MA, U.S.A, July 2003.

[5] F. Van Scoy, D. McLaughlin, and A. Fullmer, "Auditory Augmentation of Haptic Graphs: Developing a Graphic Tool for Teaching Precalculus Skill to Blind Students," in *Proc. Eleventh Int. Conf. on Aud. Disp. (ICAD)*, Limerick, Ireland, July 2005.

[6] K. G. Snook, "A Continuum of Choice: Instructional Techniques in Undergraduate Mathematics," in *MAA Notes*, Vol. 61, *Changing Core Mathematics,* C. Arney and D. Small, Eds. Washington, D.C.: Mathematical Association of America, 2002, pp. 143-149.

[7] D. Cohen, ed., *Crossroads in Mathematics*. Memphis: American Mathematical Association of Two-Year Colleges, 1995.

[8] S. M. Hetzler and R. M. Tardiff, "A Rule of Five," Maryland-District of Columbia-Virginia Mathematical Association of America Section Meeting, Williamsburg, VA, U.S.A., April 1997, http://faculty.salisbury.edu/~smhetzler/ruleof5.

[9] S. M. Hetzler and R. M. Tardiff, "Two Tools for Integrating Sonification into Calculus Instruction," in *Proc. Twelfth Int. Conf. on Aud. Disp.* (ICAD), London, England, June 2006.

[10] D. Cabrera, S. Ferguson, and G. Laing, "Considerations Arising From The Development Of Auditory Alerts For Air Traffic Control Consoles," in *Proc. Twelfth Int. Conf. on Aud. Disp. (ICAD)*, London, England, June 2006.

[11] J. Blauert, Spatial Hearing, Cambridge MA, MIT Press, 1997.

[12] D. McGookin and S. Brewster, "Contextual audio in haptic graph browsing," in *Proc. Twelfth Int. Conf. on Aud. Disp. (ICAD)*, London, England, June 2006.

[13] J. Flowers, personal communication, July 2005.

[14] M. A. Nees and B. N. Walker, "Relative intensity of auditory context for auditory graph design," in *Proc. Twelfth Int. Conf. on Aud. Disp. (ICAD)*, London, England, June 2006.

[15] H. Palomäki, "Meanings conveyed by the simple auditory rhythm, " in *Proc. Twelfth Int. Conf. on Aud. Disp. (ICAD)*, London, England, June 2006.

[16] A. Sándor and D. M. Lane, "Sonification of Absolute Values with Single and Multiple Dimensions," in *Proc. Ninth Int. Conf. on Aud. Disp. (ICAD)*, Boston, MA, U.S.A., July 2003.

[17] M. T. Dvorak, private communication, May 2004.