# Manipulating Trigonometric Expressions Encoded through Electro-Tactile Signals

Tatiana G. Evreinova
Department of Computer Sciences
FIN-33014 University of Tampere, Finland
358-3-3551-8569
Tatiana.Evreinova@cs.uta.fi

## ABSTRACT

Visually challenged pupils and students need special developmental tools. To facilitate their skills acquisition in math, different game-like techniques have been implemented. Along with Braille, the electro-tactile patterns (eTPs) can be used to deliver mathematical content to the visually challenged user. The goal of this work was to continue an exploration on non-visual manipulating mathematics. The eTPs denoting four trigonometric functions and their seven arguments (angles) were shaped with designed electro-tactile unit. Matching software application was used to facilitate the learning process of the eTPs. The permutation puzzle game was employed to improve the perceptual skills of the players in manipulating the trigonometric functions and their arguments encoded. The performance of 8 subjects was investigated and discussed. The experimental findings confirmed the possibility of the use of the eTPs for communicating different kinds of math content.

## Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/methodology, Prototyping.*

## General Terms

Measurement, Performance, Design, Experimentation.

## Keywords

Trigonometry accessibility, visually challenged people, electro-tactile signals

## 1. INTRODUCTION

It is a great challenge for the scientists to efficiently encode semantic meaning of the mathematical formulas for visually impaired pupils because of its implicit visual nature and distinctive spatial arrangement. Recently implemented various assistive techniques dealing with browsing through mathematical content by means of voice [6, 7, 8, 9, 12, 13] and/or refreshable tactile code output [1, 2, 4, 10, 11] can partially augment the opportunities of the blind and visually impaired pupil in learning to comprehend the structure of the algebraic and trigonometric notions. The sighted reader can quickly overview the whole pattern of the mathematical formulas and analyze what kind of strategy would be appropriate to apply for solving the given task based on his/her knowledge and previous experience. The visually challenged reader often gets very poor control but large cognitive overload over the flow of math content being transcribed for the residual modality which can substitute for the lack of vision. The part of cognitive resources has to be redirected to filtering symbolic concepts, which are presented in an inappropriate and unnatural way. Therefore, visually impaired pupils most often misunderstand or experience difficulty to get back “the sense” of the overall structure of the encoded complex equation if they became suddenly interrupted during the reading.

Research in electro-tactile pattern perception has shown that an activation of the occipital and posterior parietal cortexes of the occipital and parietal lobes in blind and visually impaired subjects with the use of electro-tactile signals leads to the simultaneous activation of the resources of visual cortex trained and, thus, provides multisensory enhancement of acquisition and comprehension of the tactile information encoded.

Guided by these reasoning, in our previous study we were aiming at finding the appropriate alternative for encoding elementary math symbols and arithmetic operators easily manageable through electro-tactile patterns (eTPs). The results obtained have shown that the assistive electro-tactile signals were beneficial for that purpose and upon sufficient learning and training might be used to communicate algebraic content as well.

Taking all of the above into consideration, in the present study we continue an exploration on encoding and manipulating math notions by means of the electro-tactile patterns. In Section 2, we present the apparatus used to shape eTPs encoding trigonometric functions such as sine, cosine, tangent and cotangent and their arguments (angles 0, 30, 45…270dgr.). The description of the matching software application designed for training the user to learn and memorize the developed signals candidates, the procedure of the experiment and an overview of the obtained results are reported in Section 3. Section 4 illustrates the permutation puzzle game technique designed to train the user to solve trigonometric expressions presented through the eTPs, and the results of the test. In Section 5 we discuss and summarize issues discovered regarding the capability of the participants to perceive and comprehend semantics of the math content encoded.

## 2. METHOD DESIGN

### 2.1 Participants

Eight unpaid volunteers (five males and three females) participated in the study. The age of the subjects ranged from 22 to 52 years with the mean age of 34. None of them had previous experience with the use of electro-tactile display techniques. None of participants had health or skin sensitivity problems that could hamper their participation in the two present experiments. The participants had corrected to normal vision. Sighted subjects were chosen to evaluate benefits and lacks of the proposed method. To

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.
*ICMI'08*, October 20-22, 2008, Chania, Crete, Greece.
Copyright 2008 ACM 978-1-60558-198-9/08/10…$5.00

avoid cognitive overload in the puzzle game experiment, the subjects first mastered the use of trigonometrical formulae.

## 2.2 Apparatus

The hardware used in the experimental setup was an Acer TravelMate C102Ti laptop running Microsoft Windows XP TabletPC Edition. The stylus functionality in this model is implemented using a Wacom 10.4" module. To provide the electro-tactile sensations throughout two experiments, the stylus was coated with soldered double-strip ring's type copper foil electrodes as it is shown in Figure 1.

**Figure 1. Stylus coated with electrodes.**

The electro-tactile unit was implemented and used to produce predefined parameters of electro-tactile signals. The parameters of the current pulses were stabilized and controlled through the USB port of the PC.

The basic concept of the electro-tactile stimulation is explained in Figure 2. An external load $R_Z$, which is presented by skin impedance measured between electrodes $D_1$-$D_2$ and usually is varied within a range 7.5-200 kOhm, is connected with the output of the current sources $J_1$ and $J_2$. Each of these current sources provides initial current of 0.7 mA through resistors $R_1$ and $R_2$, herewith $R_1 >> R_Z$ and $R_2 >> R_Z$. At that, potentials $U_1$ and $U_2$ are equal. The resulting current J applied in external load ($R_Z$) has a zero value. The current direction (polarity) depends of the state of the switches $T_1$ and $T_2$.

To shape the direct polarity of the current pulses switch $T_1$ shortcuts resistor $R_1$. The current pulses of the reverse polarity are being shaped when switch $T_2$ shortcuts resistor $R_2$. In a case of shaping the current pulses of direct polarity, the current through external load ($R_Z$) is provided by the output of the source $J_2$. The current pulses of reverse polarity are being shaped with the source $J_1$. The control of the switches $T_1$ and $T_2$ is programmatically carried out using the USB port and optocouplers (SFH615A).

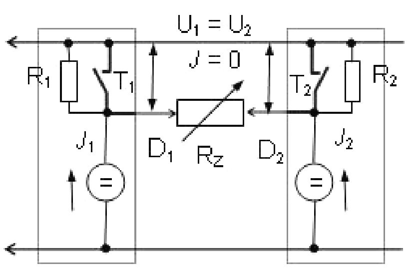


**Figure 2. Shaping the current pulses of the direct and reverse polarities.**

## 2.3 Designing electro-tactile signals

The software "ePattern constructor" was implemented and used to produce and edit bipolar or/and monopolar basic and composite eTPs controlled through parallel port with the help of electro-tactile unit described in subsection 2.2. The software was created in Microsoft Visual Basic 6.0 program environment. Upon the program start, the electrical pulses can be felt through the electrodes when the person holds the stylus. The experimenter can manipulate the software controls in order to change the parameters of both the basic and composite electro-tactile patterns such as an amount, intensity, polarity, and delay between the pulses and save all the parameters in a log file. Later, this file can be loaded and executed within the application.

Kaczmarek et al. [5] in their research used the fingertip to investigate the perception accuracy of the scatterplots. They indicated that negative monopolar pulses produce a weaker, more diffuse sensation different in perceptive quality from these of the positive monophasic pulses. As in our research the fingertips of the subjects were used for electro-tactile stimulation, all the eTPs encoding trigonometric expressions were shaped employing the positive monopolar current pulses.

The software "tPattern constructor" was used to adjust the parameters of eTPs. The eTPs designating arguments were composed in such a way that they all would have approximately the same duration about 200 ms. The eTPs denoting trigonometric functions had approximately the same duration of about 50 ms. Design features of the eTPs are presented in Tables 1 and 2.

Table 1. **Design features of the eTPs designating the trigonometric functions**

| **Function** | **Structure of the electro-tactile pattern** | | | | **Percept evoked in fingertips** |
|---|---|---|---|---|---|
| | D1 | +On1 | -On1 | Off1 | |
| sin | 2 | 15 | 0 | 10 | doubled short tingling |
| cos | 2 | 25 | 0 | 0 | doubled short itching |
| tg | 5 | 4 | 5 | 2 | doubled long tingling |
| ctg | 5 | 2 | 2 | 5 | doubled long itching |

Table 2. **Design features of the eTPs designating the arguments of trigonometric functions**

| **Angle, degree** | **Structure of the electro-tactile pattern** | | | | **Percept evoked in fingertips** |
|---|---|---|---|---|---|
| | D1 | +On1 | -On1 | Off1 | |
| 0 | 2 | 2 | 0 | 85 | weak itching |
| 30 | 5 | 5 | 0 | 34 | intensive itching |
| 45 | 6 | 5 | 0 | 28 | prolonged intensive itching |
| 60 | 6 | 2 | 0 | 30 | prolonged intensive tingling |
| 90 | 7 | 2 | 0 | 26 | doubled weak vibratory |
| 180 | 14 | 2 | 0 | 12 | doubled intensive vibratory |
| 270 | 12 | 5 | 8 | 2 | doubled weak vibratory turning into doubled intensive vibratory |

## 3. MATCHING SOFTWARE APPLICATION “ePATTERN”

The matching software application “ePattern” included two phases. In the 1st phase (training) the subject had to memorize the eleven eTPs encoding trigonometric functions and their arguments which were associated with the digital keys of the virtual keypad. By clicking the virtual key encoding angle or trigonometric function and grasping the pen coated with electrodes, the subject will initialize the eTP and feel corresponding electro-tactile sensations elicited. The trigonometric combination selected by the participant for memorizing will be displayed inside the grey label located below the virtual keypad (see Figure 3). The subject could explore the keys of the virtual keypad as many times as needed.

After remembering eTPs, the participant started the 2nd phase of the test (matching) by clicking the spacebar. The white and the grey labels appeared below the virtual keypad (see Figure 4). Clicking the grey label started eTP designating the argument, trigonometric function or entire trigonometric expression which subject has to recall. By clicking the grey label and grasping the pen, the subject perceived the eTPs encoded. The participant imagined or recalled which signals might be used to form such a sensation. Then s/he has to rebuild math symbols by clicking the appropriate virtual keys. The subject’s assumption appeared inside the white label. When the eTP associated with the grey label resembled the combination selected by the player and being visible inside of the white label, the grey virtual label had a yellow shine and the positive speech remark was heard. In a case of error, the shine was red and accompanied with the error sound. The same combination was randomly selected and presented to the player again later. The match-mismatch paradigm, the visual confirmation cues and speech remarks used in the matching phase of the test should encourage better learning and memorizing of the eTPs.

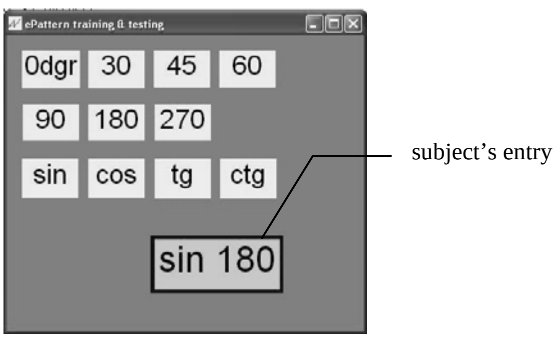


**Figure 3. The spatial layout of the testing software “ePattern” during the training phase of the experiment.**

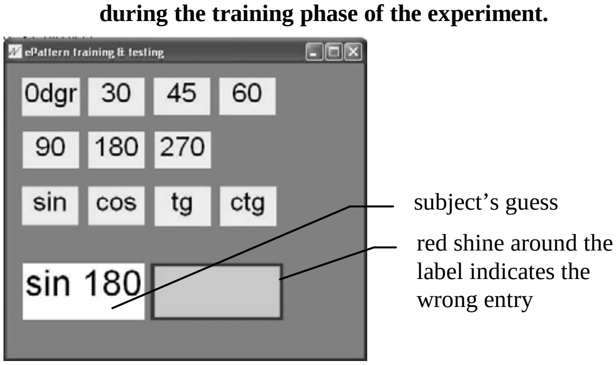


**Figure 4. The spatial layout of the testing software “ePattern” during the matching phase of the experiment.**

All the data, the number of repetitions per signal in the training and matching phases of the test, and the recognition errors committed during the matching phase were automatically collected and stored in a log file for further analysis. Thus, there was a possibility to estimate the perceptual-cognitive difficulty of the eTPs created.

### 3.1 Procedure

The subjects were tested individually. Prior to data collection, the experimenter briefly introduced the matching software implemented and the instructions concerning the overall testing procedure.

The experiment was carried out using a pen coated with the electrodes connected with electro-tactile unit, and the tablet PC. The subjects were told that they should feel electro-tactile sensations while holding the pen. They were asked to leave the hand relaxed while grasping the stylus and to explore the virtual keypad of the matching software application relying on electro-tactile sensations. In the case when a participant had a dry skin problem, a moisturizing hand cream was used for 10 minutes before the test started. Subjects were also advised to use their thumb and index fingers of the right hand when holding pen and exploring virtual keypad. The participants were then allowed to familiarize themselves with the feel of the electro-tactile patterns and to play a “warm-up” trial game. After that, the participants could ask questions if they felt that some steps in the testing procedure required more clarification.

The test sessions were scheduled from Mondays to Thursday during two weeks. Each subject completed four sessions during first week of the test and the other four sessions in the following week after a 3-day break with no more than one session per day. A session lasted one hour in average.

One test session consisted of three blocks. The one test block supposed the successful resolving the matching case as much as 5 times, that is, each subject completed the matching test 120 times in total (8 test sessions × 15 times of completing the matching case per one test session). The subjects could rest as desired between trials; therefore none of them reported loss or decrease of electro-tactile sensation throughout the testing.

### 3.2 Learning and matching electro-tactile signals

The average number of repetitions required to learn and memorize the eTPs encoding trigonometric functions and their arguments during the training phase of the test (the 1st, 2nd, 3rd and 4th test sessions, novice condition) by the subjects are presented in Figures 5 and 6. The testing subjects memorized and easier recalled the eTPs designating trigonometric functions and having the shortest duration of about 50 ms. In the 1st test session, electro-tactile patterns encoding four trigonometric functions (sine, cosine, tangent and cotangent) resulted in as much as 4, 2, 3, and 4 repetitions in an average, and by the 4th test session the subjects made only 1, 1, 1, and 2 repetitions to recall these sensations accordingly. Electro-tactile patterns encoding functions such as cosine and cotangent producing doubled short and doubled long itching sensations were the easiest electro-tactile patterns for the subjects to memorize right in the 1st test session of the training phase of the game (see Figure 6).

As it can be seen from Figure 5, the number of repetitions made by subjects to memorize the eTPs encoding zero and 270 degrees angles and producing easily perceptible and recognizable weak itching and doubled weak vibratory turning into doubled intensive vibratory sensations was steadily smallest among the repetitions committed by subjects to memorize the eTPs encoding the other six angles throughout the 1st week of testing and varied from 12 to 14 and from 10 to 14 in the 1st test session (i.e., the number of repetitions varied from 12 and 10 as a minimum value to 14 as a maximum value) and from 4 to 7 and from 4 to 5 in the 4th test session (i.e., the number of repetitions varied from 4 as a minimum value to 7 and 5 as a maximum value) correspondingly in the training phase of the test.

The eTPs encoding 30 and 45 degrees angles producing intensive and doubled intensive itching sensations, and having duration of about 200 ms, resulted in the highest number of repetitions varied from 26 to 29 and from 19 to 21 in the 1st test session and from 5 to 7 and from 7 to 9 accordingly in the 4th test session in the training phase of the test. These eTPs appeared to be easily perceptible and recognizable when they were presented to the subjects alone but difficult to distinguish within the composite pattern when presented together with trigonometric function cosine encoded with the eTP producing doubled short itching sensation during the matching phase of the test (see Figure 5).

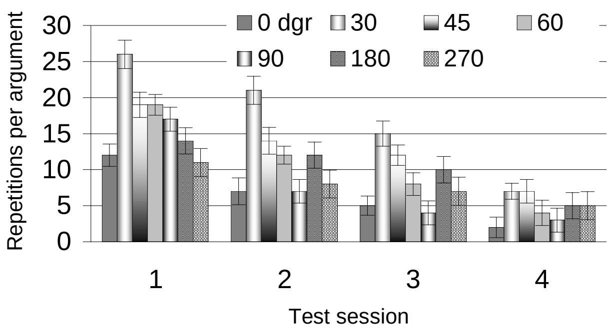


**Figure 5. Average number of the repetitions needed to memorize encoded arguments during the training phase of the experiment, the 1st week of testing.**

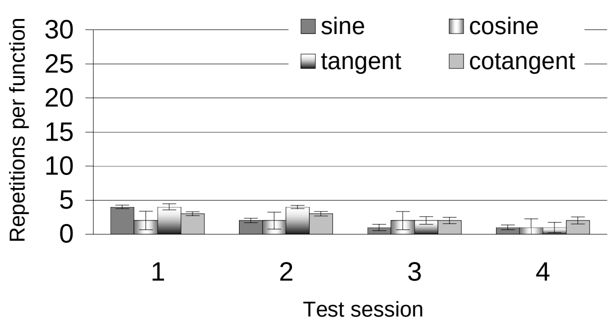


**Figure 6. Average number of the repetitions needed to memorize encoded trigonometric functions during the training phase of the experiment, the 1st week of testing.**

This is because the test subjects experienced difficulties to distinguish a tiny perceptual difference between these three gradations of the "itching sense" eliciting with a sequence of the eTPs.

The electro-tactile patterns encoding the 60, 90 and 180 dgr. angles and producing prolonged intensive tingling, doubled weak and intensive vibratory sensations were well enough perceptible and recognizable sensations and resulted in as much as 19, 17 and 14 repetitions in an average in the 1st test session. By the 4th test session of the training phase the subjects made only 4, 3 and 5 repetitions to recall these sensations accordingly (see Figure 6).

Figure 7 demonstrates that the number of repetitions required to memorize the eTPs encoding seven arguments decreased significantly to the end of the 2nd testing week and was 1 - 7 in the 8th test session vs. 12 - 26 in the 1st test session. As it can be seen from Figure 8, the number of repetitions required to memorize the eTPs encoding four trigonometric functions was the smallest, of only 1, in comparison to their arguments required to learn and memorize the eTPs encoding angles in the 8th test session. The ANOVA analysis has shown that the novice-to-expert transition was significantly above chance when the results obtained from the 1st and 8th test sessions were statistically assessed and compared ($F = 1.47$; $p < 0.001$ for eTPs encoding angles; $F = 1.87$; $p < 0.001$ for eTPs encoding trigonometric functions).

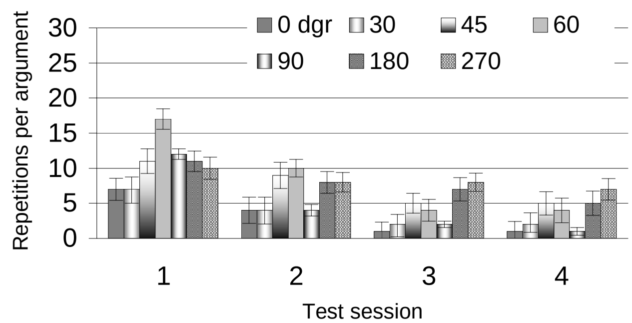


**Figure 7. Average number of the repetitions needed to memorize encoded arguments during the training phase of the experiment, 2nd testing week.**

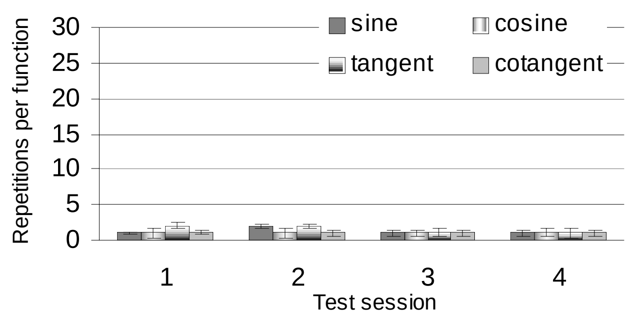


**Figure 8. Average number of the repetitions needed to memorize encoded trigonometric functions during the training phase of the experiment, 2nd testing week.**

Matching a trigonometric expression encoded by means of the eTPs, the total number of the repetitions varied from 1 to 3 in the 8th test session, when angles alone or in the combination with trigonometric functions were used. The mean recognition error rate was nearly 4.75% in the 1st test session and decreased to only 1.45% in the 8th test session of the matching phase of the test.

# 4. ELECTRO-TACTILE SIGNALS IN THE PUZZLE GAME APPLICATION

## 4.1 Puzzle game and interaction style

The distinctive feature of a permutation puzzle is a sequential swap of the corresponding cells. The permutation puzzle "Equations in Mind" composed the virtual rectangular grid consisting of three by three cells. The underlying assumption was that such a grid would allow keeping reasonable cognitive load. The rectangular grid was used to simplify a mental image of the game field. Three grid cells always contained trigonometric functions (sine, cosine, tangent or cotagent), another three grid cells comprised arguments of the trigonometric functions and three other grid cells contained values of the trigonometric functions given in combination with corresponding argument added by equal sign. The task of the player was to explore puzzle grid and rebuild three trigonometric expressions by doing swapping of the corresponding grid cells. Each grid cell value was coupled with corresponding eTP.

The experiment was carried out using a pen coated with the electrodes and connected with electro-tactile unit generating eTPs, and the puzzle game software installed on the tablet PC. When a virtual pointer of the pen entered a grid cell, the player initialized electro-tactile signal associated with a cell value. The player could inspect each cell of the virtual grid as many times as needed. S/he would need to reconstruct the mental model of the puzzle based on exploration of the puzzle cells and choose a right sequence of moves to solve the puzzle making a minimum number of swaps. Upon building a mental image, the player could make a move by swapping corresponding grid cells. By the end of each gameplay, the player heard short speech message complimenting him if the number of swaps made to solve the puzzle was less than 10, and encouraging to manage better with the next automatically initiated puzzle if the number of swaps made to solve the puzzle exceeded twelve.

## 4.2 Gameplay procedure

The subjects were tested individually. Prior to data collection, the experimenter briefly introduced the puzzle game application and the instructions concerning the overall testing procedure.

The subjects were told that the pen movements across the cells of the puzzle grid will be accompanied with electro-tactile patterns. Subjects were advised to use the thumb and index fingers of their right hand when holding pen. The participants were then allowed to play a “warm-up” game. After that, the participants could ask questions if they felt that some steps in the testing procedure required more clarification.

In a case when participant had a dry skin, the special moisture hand cream was used 10 minutes before the gameplay had started.

The entire experiment took eight days. The test sessions were accommodated to the participant’s daily schedules with no more than one session completed per day. A session lasted one hour in average. Each subject played 20 games in each session. Each game had to be concluded with successful solving of the permutation puzzle. That is, the data of eight subjects were collected concerning 160 trials in a total (8 test sessions × 20 games). To avert excessive fatigue of the player at the same time, the subjects could rest as desired between trials.

The adopted setup was considered as optimal to test how easily the players could use the electro-tactile signals associated with the virtual grid cells and which the players were trained to recognize in previous experiment, what kind of behavioral strategy they have developed to solve the puzzle using a minimum number of swaps.

## 4.3 RESULTS

### *4.3.1 Rebuilding trigonometric expressions*

Figure 9 shows the average number of the swaps made by the players to solve the puzzles generated throughout eight test sessions. With acquiring the practice in solving the puzzle technique, the players progressed through the experiment.

In the 1st test session, the players made 16 swaps in average to solve the puzzle while by the end of the 2nd testing week they were needed to make only 7 moves in an average to complete the game case. The ANOVA analysis of variance and the paired-samples t-test revealed a significant difference between the average number of permutations made by the subject to rebuild trigonometric expressions in the 1st and in the 8th test sessions ($F = 4.79$, $t(7) = -1.45$, $p<0.001$).

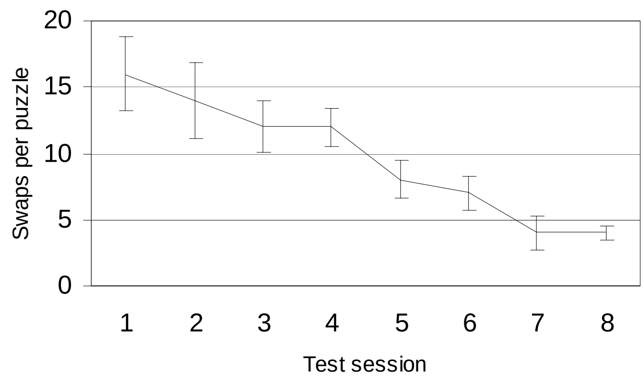


**Figure 9. Decreasing a number of swaps with acquiring practice.**

In the beginning of experiment the players committed too many redundant moves. Then, the players made the thorough tactile inspection of the each cell of the virtual grid to analyze eTPs and to discover which trigonometric functions belonged to which cell. This way the subjects have created mental image of the virtual puzzle and then they rebuilt trigonometric expressions by swapping the grid cells in a short time period.

### *4.3.2 Gameplay completion time*

The total gameplay completion time the players spent to solve the puzzles in the 1st and 2nd weeks of the testing included inspection of the virtual grid and rebuilding three trigonometric expressions by swapping corresponding cells.

The variations in the gameplay completion time values were mostly influenced by perceptual abilities of the players to perceive and distinguish eTPs denoting trigonometric functions. Figure 10 illustrates the average gameplay completion time spent by the players throughout eight test sessions. The analysis of the data indicated that the novice-to-expert transition happened already in the 4th test session. In the 1st test session, the players were required of about 190 s to solve the puzzle while in the 4th test session they have spent about 75 s to complete the game case. By the time the players had already played 140 games, their performance had improved by 7 times. An average gameplay completion time decreased up to only 25 s. The ANOVA analysis of variance and the paired-samples t-test revealed a significant difference between the average gameplay completion times needed to rebuild trigonometric expressions in the 1st and in the 8th test sessions ($F = 32.69$, $p<0.001$).

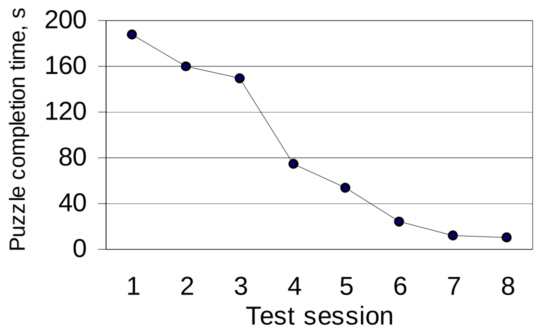


**Figure 10. Puzzle game completion time.**

## 5. CONCLUSIONS

Suitable encoding the math content for visually impaired users is very challenging for the scientists because of its implicit visual nature and distinctive spatial arrangement. The present study was aiming at an exploration on non-visual manipulating mathematics by making use of the two implemented software applications. Four electro-tactile patterns denoting trigonometric functions having duration of about 50 ms, and seven electro-tactile patterns denoting their arguments and having duration of about 200 ms, have been explored in two interaction scenarios.

The analysis of the data collected indicated that when learning encoded trigonometric expressions using the matching software application “ePattern”, the testing subjects better memorized and easier recalled the eTPs having the shortest duration of about 50 ms, especially those encoding cosine and cotangent.

Among the eTPs encoding arguments, the most perceptible and recognizable were the encoded zero and 270 degrees. They resulted in the smallest number of repetitions already in the 1st test session of the training phase of the matching experiment. The electro-tactile patterns encoding the 60, 90 and 180 dgr. angles were well perceptible and recognizable sensations and resulted in more than 10 repetitions in an average in the 1st test session of the training phase of the test.

The eTPs encoding the angles of 30 and 45 degrees appeared to be easily perceptible and recognizable as separate stimuli but difficult to distinguish within the composite pattern when presented together with trigonometric function cosine during the matching phase of the test. This is because there was a tiny perceptual difference between the three gradations of the “itching sense” eliciting with these three eTPs. For this reason, they resulted in the more than 19 repetitions in the 1st test session in the training phase of the test. In the future perspective, the structure of the current pulses denoting these arguments has to be improved.

In the matching phase of the experiment, the subjects used very small number of repetitions of only 1-3 and resulted in a steadily low recognition error rate of 1.45% in the 8th test session to match the trigonometric expression comprising angle given alone or together with the trigonometric function of the angle.

The average number of permutations made by the subject to rebuild trigonometric expressions using puzzle game “Equations in Mind” application decreased fourfold and the task completion times decreased by 18 times to the 8th test session .

We suppose that upon an appropriate learning and training, the electro-tactile patterns could be employed to make comprehension of different kinds of the mathematical content easier to visually challenged people.

## 6. ACKNOWLEDGMENTS

This work was financially supported by the Academy of Finland (grant 115596).

## 7. REFERENCES

1. Archambault, D., Stöger, B., Batusic, M., Fahrengruber, C. and Miesenberger, K. Mathematical working environments for the Blind: what is needed now? Proc. of the 7th IEEE International Conference on Advanced Learning Technologies (ICALT 2007), July 18-20, 2007, Niigata, Japan
2. Barry, W. A., Gardner J. A. & Raman, T. V. (1994) Accessibility to Scientific Information by the Blind: Dotsplus and Aster Could Make it Easy. Proceedings of the 1994 CSUN Conference on Technology and Persons with Disabilities, Los Angeles, CA.
3. Karshmer, A.I., Gupta, G., Geiger, S., and Weaver, C., Reading and Writing Mathematics: The MAVIS Project, BIT (Behaviour & Information Technology), January 1999.
4. Karshmer, A.I., Gupta, G., Pontelli, E., Miesenberger, K., and H-F Guo, "The Development of a Tool to Enhance Communications Between Blind and Sighted Mathematicians, Students and Teachers: A Global Translation Appliance," Proceedings of the HCI Conference, New Orleans, 2001.
5. Kaczmarek, K. A., Tyler, M. E., and Bach-y-Rita, P., Electro-tactile haptic display on the fingertips: preliminary results. In Proc. Of the 16th Annual International Conference IEEE 1994, pp. 940-941.
6. Kennel, A.R., "AudioGraf: A Diagram Reader for the Blind," ASSETS 96 Conference, 1996.
7. Mansur, D.,L., "Graphs in Sound: A Numerical Data Analysis Method for the Blind." Masters Thesis, University of California at Davis, 1975.
8. Reddy, H., G. Gupta, et al. (2005). Dynamic Aural Browsing of MathML Documents with VoiceXML. Human-Computer Interaction, Las Vegas, L. Erlbaum.
9. Sahyun, S., and Gardner, J., Audio and Haptic Access to Math and Science - Audio Graphs, Triangle, MathPlus Toolbox and Tiger Printer," 15th IFIP World Congress, Vienna, 1998.
10. Scadden, L. A. 1996, Making Mathematics and Science Accessible to Blind Students through Technology, in Proceedings of the RESNA '96 Annual Conference, E. Langton (Editor), Arlington, VA: RESNA Press,
11. Schweikhardt W. 8-Dot-Braille for Writing, Reading and Printing Texts which Include Mathematical Characters. In: A.D.N. Edwards, A. Arato, W.L. Zagler: Computers and Assistive Technology, ICCHP98, Wien and Budapest, 31. August - 4. September 1998
12. Stanley, P., Bledsoe, C., and Karshmer, A., Verbally Rendering Math Statements with the MathGenie Accessibility Software for the Print Impaired, Florida Tech Transfer Conference, May, 2005
13. Walsh, P., R. Lundquist, et al. (2001) The Audio-accessible Graphing Calculator. CSUN Volume, DOI: http://www.csun.edu/cod/conf/2001/proceedings/csun01.htm