Spatial Skills and Visualization Training for Future STEM Careers

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Abstract

The program, formerly known as The Mind Fitness Program, had to be renamed to avoid a registered trademark infringement. The new name is more explicit in describing the goal of the program, which is to prepare the participants for STEM careers by stimulating their spatial skills, 3D visualization, analytical abilities, pattern recognition skills, memory, attention to detail, and general mental performance of participants.

The various stages of the program have been presented in three previous ASEE papers. After a successful testing in 2022, the program has been included as part of summer camps at the DoSeum in San Antonio and in the Lunar Caves Analog Test Sites Program (LCATS) offered by the WEX Foundation. The program is also an important component of the educational activities at the DoSeum throughout the year.

The program continued to be presented at Alamo STEM Ecosystem Educator Conferences and at several local schools as an after-school optional program. One of the problems encountered was the lack of funding to support offering the program free of charge and as a result, a cost evaluation is in progress so the program may be offered for a basic fee to cover the expenses.

The number of exercises used in the program was maintained unchanged as they were designed to challenge specific areas of the brain, just as physical exercises affect various muscle groups. They are disguised as games since one of the most recent and promising trends in education is the “edutainment” concept, which combines educational content with entertaining activities so, the participants learn while having fun.

The program proved its flexibility as it was adapted to various locations, number of participants, and time intervals. The paper will present the continuation of the program, the new results, and the plans for future expansion of the program to reach a broader range of participants.

Introduction

Extensive evidence supports the effectiveness of instructing engineering students in spatial visualization skills, leading to improved outcomes. Research, spanning from the early 1990s onwards, has consistently shown that practicing and training in spatial visualization enhances performance in engineering courses and other STEM programs [1-6]. Furthermore, studies indicate that enhanced 3D visualization abilities contribute to higher retention and graduation rates, especially among underrepresented groups in the field of engineering [7-12]. New studies add more details to the growing amount of information demonstrating the need to improve the way STEM subjects are taught in schools [13-17].

As a result of these obvious needs, a new program has been developed to help prepare participants for STEM careers by enhancing various mental skills. The focus on spatial skills was expanded to 3D visualization, analytical abilities, and pattern recognition. The program has been introduced in a previous paper [18] and has seen successful implementation in multiple settings like summer camps, STEM conferences, schools, and educational events, showcasing its adaptability and diverse application.

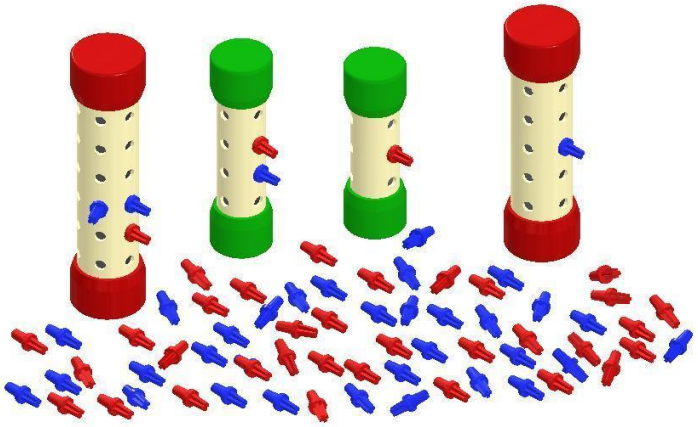
The program has been developed and continuously improved following the new findings and recommendations presented in several studies covering spatial skills and their impact on STEM education. It includes some of the suggested pedagogical play-framework approaches [19] and developing spatial concepts recommended by [20]. The pre/post-program test was developed to include a compilation of several standard visualization tests (Spatial Reasoning Test, PSVT-R, and Vanderberg MRT) and was in most part supported by the recommendations from Göktepe and Özdemir [21].

Program content analysis

The program, by design, requires a coach and is extremely flexible and adaptable to various conditions, locations, and available time schedules. The program starts with a brief presentation of the design concept and the tools and skills needed to do it successfully. This is done to help students understand the need for this kind of training. Then the program continues with the practical components. The program has eleven components divided in two categories: Core Components and Auxiliary Components. The components were selected to expose the participants to a variety of stimuli to help them improve their mental abilities.

Core Components

- **TIC TAC TOTEM**

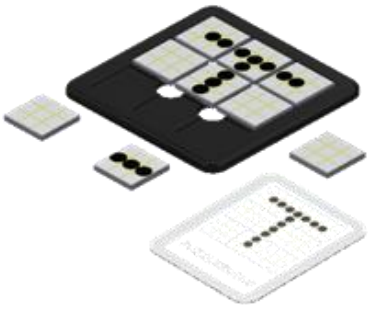


The **Tic Tac Totem** is a set of two-player games where players alternately place one peg in a hole. The winner is the first player that puts the pegs in a full formation – column, ring, or diagonal – akin to 3D tic-tac-toe. The games may also be played in a solitary mode where all pegs are inserted in the game holes. There will be one or two empty holes and each should be on one of the extreme rings. The scope of the game is to remove as many pegs as possible. A peg can be removed only by jumping over it with another peg. The jump can be horizontally on a ring, vertically on a column, or diagonally. The

jump can be only over one peg at a time and the jump can be made only into an empty hole. Ideally, the game is played until only one peg is left.

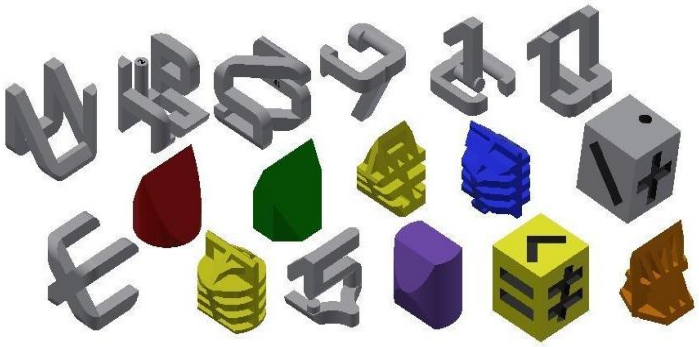
The challenge of the games is the fact that almost half of the playing area is obscured by the cylindrical body so the players must develop a mental image of the whole playing area. This set of exercises was considered important for developing spatial thinking, spatial perception, and spatial reasoning.

- **PUZZLEBUILD**



The **PuzzleBuild** enhances players' abstract thinking, pattern recognition, visualization skills, and attention to detail. This is achieved through the creation of letters and number shapes using modular components. The basic game involves the utilization of nine tiles adorned with dot designs to construct letters and numbers.

KRYPTOGLYPHS



KryptoGlyphs is a challenging and unique single and multi-player set of games that increases the players' level of abstract thinking and 3-D visualization skills. Each 3D letter module shows at least three different letters out of which at least one is a vowel. The game may be expanded to include numbers and plane geometric shapes. The concept was first presented in a book format in 2015 [22] followed by ASEE presentation [23] in 2016 and won the Best Educational Concept award at the 2017 Chicago Toys and Games Convention

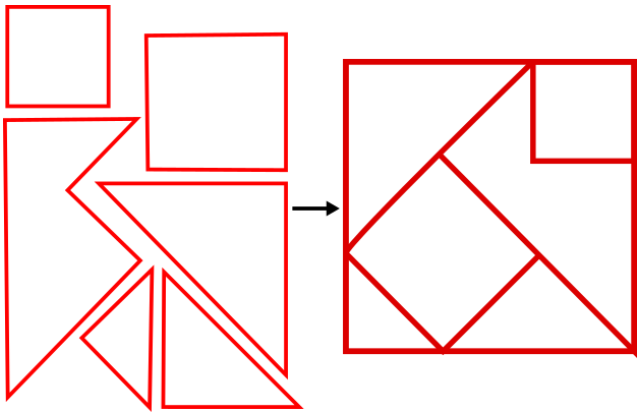
- **TOUCH'N TELL**

Touch'n Tell is a tactile recognition game in which the players attempt to name the letters they touch without seeing them. The game has two parts. One part uses cut-out letters. The second part has a disk with embossed or debossed, uppercase or lowercase letters. Each disc has on one side the outward extruded figures while the cavity figures and are on the opposite side. The first part allows the player to manipulate the cut-out letter until, eventually, the shape is recognized while the second part uses only the fixed letter contours as guidance for letter recognition.

- **COUNTING BRICKS**

Counting Bricks is a challenging and unique new set of educational activities based on popular LEGO bricks that increase the players' level of abstract thinking and visualization skills by creating 3D formations from modular components. The game is based on a new concept of visualization exercises. The concept was first presented in a book format under the title "Counting Bricks from Ancient Ruins" in 2017 [24], followed by the ASEE presentation [25] in 2020.

- **SQUARE OF SIX**

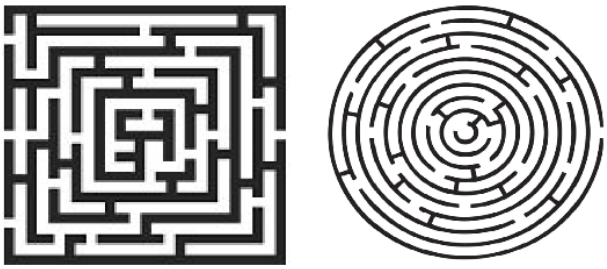


Square of Six is a puzzle of six irregular shapes that can be combined in a particular combination to create a square.

After the square configuration is memorized, the game can be expanded by tracing the outline of a new shape formed by the combined shapes and challenging another player to recreate that shape.

Auxiliary Components

- **A-MAZE-ING**



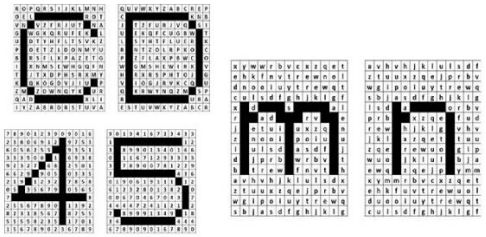
A-MAZE-ING is a game played on panels containing various shapes of labyrinths. The mazes are to be played in order from the simple ones to the more complex ones. They enhance players' problem-solving, visual motor skills, and attention to detail.

All players use the same panel and start solving the maze at the same time. The setting may be collaborative or competitive.

At a more advanced stage, the players are invited to create their own labyrinths and exchange them with other players.

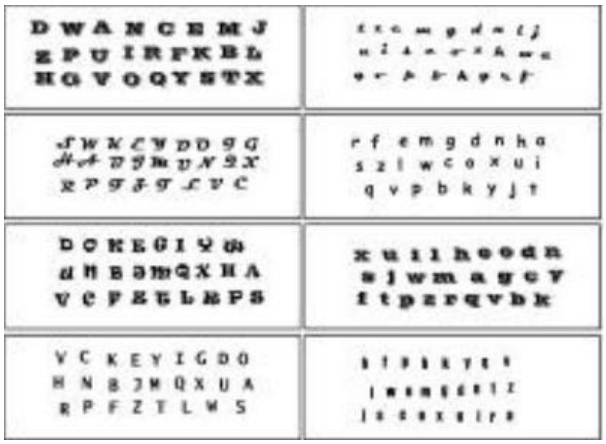
- **DOT 2 DOT**

Dot 2 Dot is a game that uses printed grid panels. The grids are filled with letters and numbers. Each grid has one letter or number arranged in a pattern that when all the squares containing it are colored it will reveal a digitized image of the respective letter or number. The game has two sets of challenges. The basic level has the colored figure the same as the revealed one. The advanced level uses the same concept but the revealed figure is always a different one from the colored one. It can be played competitively, timed, or just to reach a personal best.



- **FONT CHALLENGE**

The **Font Challenge** game *is* a challenging new and unique type of educational game that increases the players' level of abstract thinking, visualization, and pattern recognition skills using printed panels. The game uses panels filled with capital and lower-case letters printed with multiple different fonts and orientations at two scales, a large one and a small one. The players must identify random letters.



- **WORD HUNT**

The **Word Hunt** is a game played on a grid panel filled with letters. The letters displayed on the grid are either capital letters or lower-case letters.

The players are challenged to find the words in the grid. The words can be read horizontally, vertically, or diagonally in either one of the eight directions. The game can be played competitively, timed, or just to reach a personal best.

- **SCRAMBLED DROWS**

Scrambled DROWS is a game played on paper displaying apparently random letters that, when properly arranged show a regular word. Some of the letter groups are capital letters and some groups contain lowercase letters.

5 LETTERS

REGIM = GRIME; huslp = plush

6 LETTERS

CETOPK = POCKET ; penpah = happen

The players are provided with one or several scrambled words and the game invites the players to unscramble them. It can be played competitively, timed, or just to reach a personal best.

Each Core Component demands a range of different materials, each presenting distinct challenges that offer varying difficulty levels, fostering brain stimulation. On the other hand, the Auxiliary Components, primarily involve paper-based play, requiring only a pencil and an eraser.

While an optional computer with a projector and screen can be utilized for game analysis and feedback provision, it is not essential for gameplay.

Implementation settings

The program has been implemented in two kinds of settings. One setting was a one-week summer camp with five daily sessions with diverse activities scheduled from 9:00 AM to 3:00 PM. The other one was two semesters long with 12 one-hour Saturday sessions two to three weeks apart.

Although the settings were vastly different, the composition of the student population and the results were very similar. This observation may suggest that perhaps just exposure to the concepts included in the program improves the participants' spatial skills. Of course, more studies will be necessary to draw a firm conclusion.

More programs were planned, two for two elementary schools, one for a middle school, two for a local community college, all as one-week summer camps but all had to be canceled due to low enrollment and/or scheduling conflicts. All these cancellations provided strong evidence that in a market saturated with specialized camps and youth programs, there is a need for a wider range of targeted advertising and better planning and coordination with school administration and faculty.

It was recommended that regardless of the implementation setting the programs should have at least one 45 to 50 minutes session per day. Each day should start with a brief discussion regarding one of the basic elements of design and spatial visualization skills with examples. These starting-the-day discussions should help the students understand the reasons for each aspect of the training program. Once the reasons are understood the participants become more willing to engage in the program’s activities.

During one session, no more than two Core Components and one or two Auxiliary Components should be used alternately. This would prevent the participants from being bored or distracted by other activities. Phone use during sessions should be prohibited to help mitigate distractions.

DoSeum Implementation

The DoSeum is a children's museum in San Antonio [26], Texas with extensive experience leading educational camps across a variety of subjects. The DoSeum partnered with The Spatial Skills and Visualization Training for Future STEM Careers team in 2022 to test, prototype, and produce the Core and Auxiliary Components listed above. In the summer of 2023, educators at The DoSeum worked with Dan Dimitriu to design a 5-day camp to test the effectiveness of the program and its various components as "edutainment" tools.

This camp had twelve students, two instructors, and one volunteer teaching assistant. The students were aged between 8-11 years old, with most students aged between 8 and 9. Two students were diagnosed on the autism spectrum and one student was diagnosed with attention deficit hyperactivity disorder. Four of the students were female.

Students were assessed for spatial skills with a timed test on Monday before they played with any of the core components, and assessed again with the same test on Friday after completing the 4-day program. Each day began with a lecture on engineering design principles which explored the concepts of projections and their correlation with pictorial and multi-view orthographic representations.

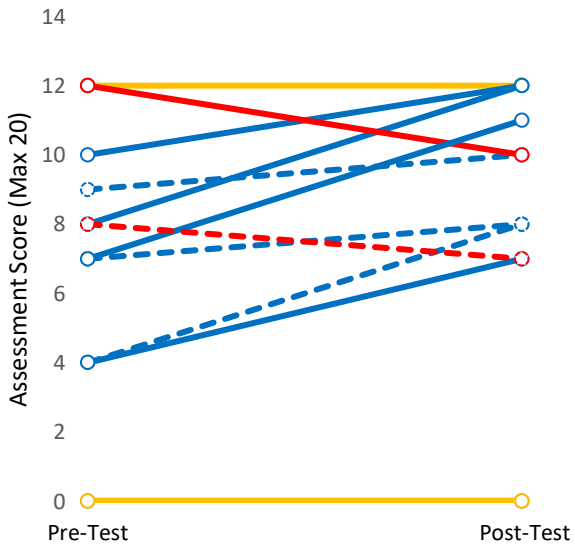
Monday	Tuesday	Wednesday
Pre-Test Design Presentation #1 Tic Tac Totem 3x3 Puzzle Build (CAPITAL LETTERS)	Design Presentation #2 Tic Tac Totem 4x4 PuzzleBuild (lowercase letters)	Design Presentation #3 3D illustration of shapes Touch-N-Tell Square of Six Introduced Ranking System
Thursday	**Friday**	**Table 1. Schedule of camp week.** Each day was from 9 AM-3 PM and included breaks for food and free exploration of the galleries at The DoSeum.
Design Presentation #4 KryptoGlyphs Ranking Attempts	Post-Test Ranking Attempts	

Table 1 shows the order that which students were exposed to the core components. Of note, when we introduced a new core component to the class, we gave students 20 minutes to explore the components and discuss strategies for success with each other.

Then we would have head-to-head competitions with Tic Tac Totem, timed challenges with PuzzleBuild and Touch-N-Tell, and team competitions with KryptoGlyphs.

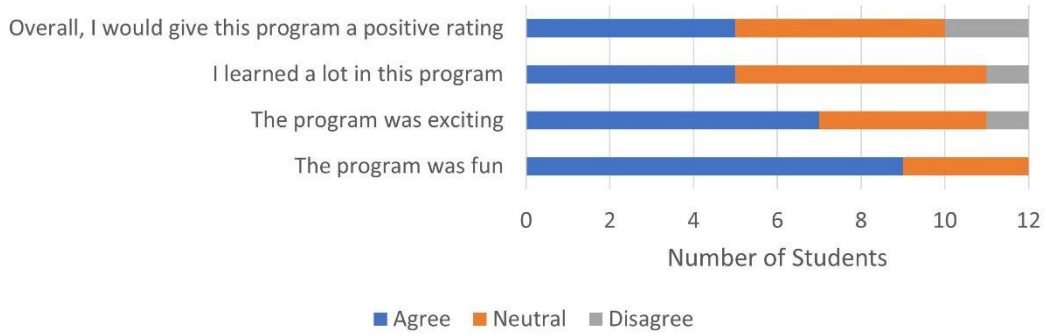
On Wednesday we introduced a ranking system to gamify how students engaged with the core components. We found the ranking system rejuvenated student interest in the core components and this lasted through the rest of the week. Ranks were loosely inspired by military terminology and corresponded to component mastery. The criteria for each rank were often subjective and improvised by the instructors, but the concept alone proved to be a powerful motivator for student engagement. For example, students could progress from private, lieutenant, general, sergeant, captain, to ultimately colonel. In Tic Tac Totem, students must win a game against a peer to achieve private, but could only become colonel by beating a teacher in the 5x5 version. Ultimately, we predict that the specifics of the ranking criteria are far less impactful than the mere concept of a ranking system; and, therefore, many different criteria combinations could be used to similarly effective results for component engagement.

The other curriculum addition outside of the core component usage was on Wednesday following Design Presentation #3 about multi-view orthographic projections. Students were instructed to retrieve an irregular 3-dimensional shape from one of the museum's exhibits and illustrate a multi-view orthographic representation of the object. This activity was well-received as students voluntarily attempted increasingly complex objects.



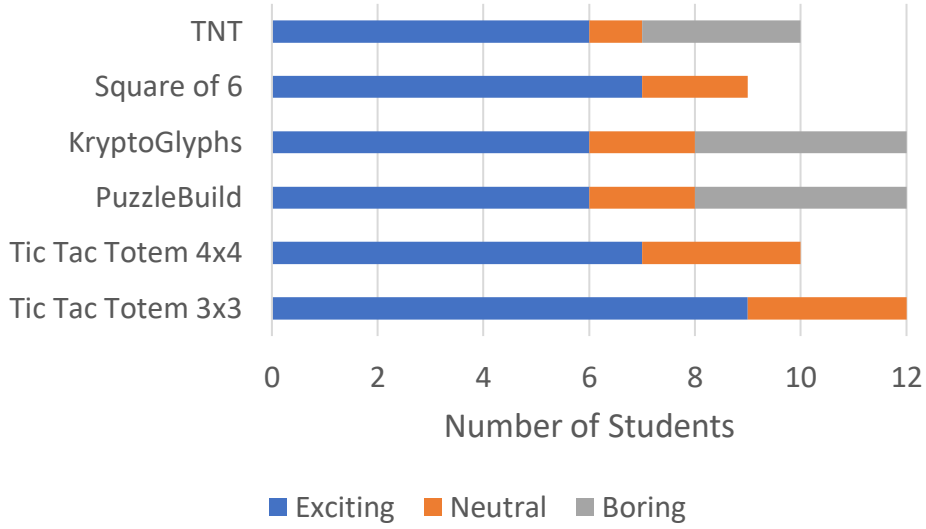
Graph 1 – Pre- and Post-Test Results for the DoSeum cohort. Solid lines represent male students. Dashed lines represent female students. Three students (orange lines) showed no improvement between pre- and post-tests (two students failed to participate in the tests and therefore scored 0 on pre- and post-tests). Two students (red) performed worse on the post-test. The other seven students (blue) improved their scores between pre-and post-tests.

At the end of the program, a Program Evaluation Questionnaire (Appendix 1) was administered, and the main results are presented in Graph 1. Most students showed improvement in spatial reasoning after completing the 1-week program. Additionally, we asked each student to evaluate the overall program (Graph 2) and the individual core components (Graph 3). Overall, students found the program fun, but fewer than half felt they learned "a lot" or would give the overall program a positive rating.



Graph 2 – Overall Program Evaluation by the DoSeum cohort.

Much of the program and the general concept of spatial reasoning was novel to students which could explain the contradiction between their low, self-reported feeling of learning and their quantitatively improved test results presented in Graph 1. Additionally, students may link learning with tedious and rigid activities often associated with the standardized classroom setting. Thus, student bias may explain why students (1) showed marked improvement in their test scores, (2) rated the program as fun, yet (3) did not feel that they "learned a lot in this program."



Graph 3 – Rating of the core components used by the DoSeum cohort. Some games do not total 12 evaluations because students were instructed to answer N/A if they were absent for a particular game, and thus had not played with it.

Following the success of this camp, The DoSeum continues to implement the core components as supplemental activities in other camps across all disciplines for ages 8-11. The tic tac totem series are the most popular core-component supplemental activities – which is also reflected in Graph 3.

LCATS implementation

The LCATS Program [27], offered by the WEX Foundation, is a 3-year NASA-commissioned program that allows middle and high school students to work alongside industry professionals to tackle real-world space exploration challenges and offer solutions through an array of investigations, experiments and design projects with project-based learning. The curriculum and project themes for each year build upon each other for a comprehensive experience of the challenges and opportunities involved with space exploration. Concepts addressed by the effort include the development of rockets, robotics, space construction and space architecture for habitation in Earth's orbit and within lunar lava tube caves on the Moon. LCATS takes place during the school year on alternating Saturday mornings for 2 sessions a month, with a total of 16 sessions a school year.

Each 4-hour long Saturday session includes 1-2 hours of the spatial skills and visualization training module to enhance and stimulate students' skills in spatial awareness, 3D visualization, analytical abilities, abstract thinking, pattern recognition, memory, attention to detail, and overall mental performance. Training in these skills at a young age provides students a skill-set that will benefit them throughout their careers in the STEM field of their choosing.

The program was successfully tested in 2022 during a year 3 LCATS cohort. Since then, the program has gained outstanding recognition by the community and has been built to stay into the LCATS curriculum.

It is important to note that the components of the training program do not rely on digital tools, but use a variety of physical exercises designed to challenge different parts of the brain; just as physical exercises affect various muscle groups. The exercises are disguised as hands-on games, aligning with the project-based structure of the LCATS program. It combines educational content with entertaining activities, allowing the participants to gain essential non-digital spatial awareness skills while simultaneously having fun.

The LCATS Program currently serves a Year-1 (Y1) Cohort of 30 students, 4 staff, and 3 volunteer assistants. The students are between grades 7-10, and they all come from a different middle school/high school. Out of the 30 students, 2 have ADHD and 1 has dyslexia. There at 16 girls and 14 boys. Due to the unique age range of participants in the LCATS program, it frequently serves as their initial exposure to STEM programs. Numerous aerospace and industry professionals, as well as the LCATS Instructors, have remarked on the students' ability to grasp these important engineering concepts at exceptionally young ages.

Students were assessed for spatial skills with a timed test on the first Saturday of their first year in the program, before they played with any of the core components, and will be assessed again with the same test on the final Saturday of the first year. They will be tested again at the beginning/end of their second year, and the beginning/end of their final (3rd) year in the LCATS Program. The goal of each year is for students to show an

increase in spatial awareness, and use the skills they are learning to assist them in engineering and architectural problem-solving.

The games and topics covered during each session of this year first year cohort are presented in Appendix 2.

Each session begins with a lecture presentation on an engineering design principle that correlates to the activity for the day. This presentation promotes student-led discussion about the principles they are learning, and how they can implement this learning into real-world challenges.

As shown in the schedule, students will spend multiple sessions exploring each hands-on activity. They will discuss the concepts addressed when playing the game properly, and will be given time to explore efficient, creative ways to master their own implementation of the games.

So far, the students have shown a large interest in the program and have shown improvement in producing effective design concepts. Their skills in freehand sketching over the last 6-months has increased, shown when the students competed in the Texas Alliance for Minorities in Engineering (TAME) Design Competition in January, 2024. The LCATS students produced award-winning robotic designs, taking 1st, 2nd, and "Engineering Mindset" awards.

The implementation of the Spatial Skills and Visualization Training Program will continue in each year (1,2,3) of the LCATS program. Students' skills will be evaluated at the start and finish of each year, and the curriculum for their Years 2-3 will be adjusted according to their strengths and weaknesses.

Future Plans

Initially, the program was started at San Antonio College and was designed to serve its engineering program students. Gradually, some of the exercises were expanded to the EDGE program [28], other local community colleges, and several other educational organizations interested in improving their students' performance.

One of the major roadblocks for the program's expansion was lack of funding. All the ISDs and schools where the program was presented were impressed by the program's potential but all complained about lack of funding to support new programs not aligned with any existing curriculum. With teaching loads continuously increasing and funding continuously reduced, there is understandably little to no incentive to start a new program that required extra time and effort from teachers. The possibility of expanding the program with fee-based access program was considered but has not yet been pursued. The issue about the affordability and availability of the program for all participants is the main reason.

In advancing the future plans for the Spatial Skills and Visualization Training for Future STEM Careers program, strategic partnerships with UT Austin [29] and Rice University's Office of STEM Engagement [30] are poised to play a pivotal role. The establishment of

a Research Experience for Teachers (RET) Program [31,32], a collaborative effort with these esteemed institutions, seeks to empower educators in seamlessly integrating the Spatial Skills training into their curricula. This partnership not only provides a platform for training but also opens avenues for securing funding through sponsorship and grants offered by these organizations. The ongoing collaboration will facilitate research-driven enhancements, ensuring the program stays abreast of the latest pedagogical and STEM education research, thereby maintaining its effectiveness and relevance.

This emphasis on partnerships extends to local Career and Technical Education (CTE) programs [33], where collaboration can lead to the integration of the Spatial Skills program into technical education pathways. By aligning with CTE initiatives, the program can offer specialized modules that cater to the unique needs of these pathways, enhancing students' spatial skills for technical careers. Furthermore, partnerships with CTE programs create opportunities to access funding through sponsorship and grants, reinforcing the financial sustainability of the program.

Another possible future partnership is in the works with TERC (Technical Education Research Centers) [34] to expand our program exposure to multiple centers so, together, we can reach a common goal of improving and transforming STEM education, making STEM more accessible to all learners, and igniting passion for lifelong learning.

A parallel initiative involves forming a strategic alliance with an engineering-focused high school to establish a pre-engineering camp. The experience gained from previous participation in the EDGE program [28] and the PREP program [35] will create a solid foundation for a long-lasting partnership. This collaborative venture, enriched by the expertise of high school faculty, ensures that the Spatial Skills program aligns seamlessly with pre-engineering curriculum objectives. As part of this partnership, exploring funding opportunities through grants and sponsorships becomes integral to sustaining and expanding the impact of the program. The envisioned pre-engineering camp aims to serve as a transformative bridge between high school and college STEM education pathways, fostering students' interest and proficiency in spatial skills.

These partnerships not only contribute to the program's financial sustainability but also reinforce its adaptability and relevance in diverse educational settings. By securing funding through sponsorship and grants from esteemed organizations, the Spatial Skills program can continue its mission of preparing participants for successful futures in STEM careers.

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APPENDIX 1

Date: _____ Age: ____

Gender: M F

DoSeum Summer Camp 9: July 31-August 04 - Program Evaluation

Please circle the choice that represents your closest opinion:

Evaluation of the program:	**Disagree**	**Neutral**	**Agree**
The program was fun	X	X	X
The program was engaging (I wanted to try all activities)	X	X	X
I learned a lot in this program	X	X	X
Overall, I would give this program a positive rating	X	X	X
Evaluation of the trainer:			
The trainer explained well what I needed to do	X	X	X
The materials were organized in a good sequence	X	X	X
The trainer was helpful in class	X	X	X
Evaluation of the content:			
The presentations were informative	X	X	X
The games were challenging	X	X	X
The evaluation test was too easy	X	X	X

Rating of individual games:

Please rate each game you played from **1** (boring) to **5** (exciting)

Tic Tac Totem	**1**	**2**	**3**	**4**	**5**	**N/A**
3x3	X	X	X	X	X	X
4x4	X	X	X	X	X	X
PuzzleBuild	X	X	X	X	X	X
KryptoGlyphs	X	X	X	X	X	X
Square of 6	X	X	X	X	X	X
TNT	X	X	X	X	X	X

What would you like to change in the program?

APPENDIX 2

LCATS Program 2023-2024

2023 Session Dates:

9/16/23 - LCATS Launch

General Presentation of my program with Questions and Answers at the end

9/30/23

- Detailed Program presentation;
- Pre-program skills evaluation test;
- Basic Tools for Design Part 1
- Teams' formation: 30 students = 3 students/team

10/14/23 - Field Trip – SCOBEE Planetarium

10/28/23

- Free Hand Sketching presentation
- **Tic Tac Totem** game presentation and training (3 x 3)
- **Letter Corral** game introduction
- Games analysis and strategies discussion

11/11/23

- Critical Thinking Presentation
- Feel Good Party
- **Tic Tac Totem** – game training (4x4)
- **Letter Corral** game training (capital letters)
- Games analysis and strategies discussion

11/18/23

- Basic Tools for Design Part 2;
- **Tic Tac Totem** game training (4 x 4)
- **Letter Corral** game training (lower case letters)
- Games analysis and strategies discussion

12/02/23 – Cave Trip

2024 Session Dates:

1/13/24

- Basic Tools for Design Part 3;
- First Free Hand Exercise
- **Tic Tac Totem** game competition (4 x 4)
- **Letter Corral** game training (numbers)

1/27/24

- Coordinates Presentation
- Free Hand Exercise with real objects
- **KryptoGlyphs** game training
- Game analysis and strategies discussion
- Random Challenges for Fun

2/10/24

- Basic Tools for Design Part 4;
- Free Hand Exercise with Real Assemblies
- First **A-MAZING** Challenge game training
- Games analysis and strategies discussion

2/24/24

- Basic Tools for Design Part 5;
- Second **A-MAZING** challenge
- **Touch'n Tell (**Individual Letters**)** game training
- Games analysis and strategies discussion

3/16/24 – Field Trip - SwRI

4/06/24

- Pictorial representations
- **Advanced Mazing** challenge
- **Dot 2 Dot** game training
- Games analysis and strategies discussion

4/20/24

- Computer Assisted Design (CAD)
- **Dot 2 Dot** Advanced game training
- **Scrambled DROWS** game training
- Games analysis and strategies discussion

5/04/24 - Student Showcase

- Post-program skills evaluation test
- Program evaluation
- **Career advice and chat**