Enhanced learning of proportional math through music training and spatial–temporal training

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It was predicted, based on a mathematical model of the cortex, that early music training would enhance spatial–temporal reasoning. We have demonstrated that preschool children given six months of piano keyboard lessons improved dramatically on spatial–temporal reasoning while children in appropriate control groups did not improve. It was then predicted that the enhanced spatial–temporal reasoning from piano keyboard training could lead to enhanced learning of specific math concepts, in particular proportional math, which is notoriously difficult to teach using the usual language–analytic methods. We report here the development of Spatial–Temporal Math Video Game software designed to teach fractions and proportional math, and its strikingly successful use in a study involving 237 second-grade children (age range six years eight months–eight years five months). Furthermore, as predicted, children given piano keyboard training along with the Math Video Game training scored significantly higher on proportional math and fractions than children given a control training along with the Math Video Game. These results were readily measured using the companion Math Video Game Evaluation Program. The training time necessary for children on the Math Video Game is very short, and they rapidly reach a high level of performance. This suggests that, as predicted, we are tapping into fundamental cortical processes of spatial–temporal reasoning. This spatial–temporal approach is easily generalized to teach other math and science concepts in a complementary manner to traditional language–analytic methods, and at a younger age. The neural mechanisms involved in thinking through fractions and proportional math during training with the Math Video Game might be investigated in EEG coherence studies along with priming by specific music.
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Keywords: Columnar cortical model; educational implications; EEG coherence studies; spatial–temporal math software; piano training

INTRODUCTION

Motivated by predictions[1] from the structured trion model[2–5] of the cortex (based on the Mountcastle[6,7] columnar organizational principle), behavioral experiments[8,9] have demonstrated a causal short-term enhancement of spatial–temporal (ST) reasoning: College students, after listening to the first 10 min of the Mozart Sonata for Two Pianos in D Major (K.448) *versus* various controls, had a subsequent short-term enhancement of ST reasoning[8,9]. An EEG coherence study[10] reported the presence of right frontal and left temporo–parietal activity induced by listening to Mozart's Piano Sonata K.448, which carried over into the ST tasks. Further recent studies[10–14] have given support for the model and the profound effect of Mozart Sonata K.448 on higher brain function. Of more interest educationally is the study[15] showing that preschool children who received piano keyboard lessons for six months improved dramatically, with the effect lasting days, on an ST reasoning task while appropriate control groups (including a control group receiving English language training on computers) did not improve significantly.

It was suggested in the Preschool Study[15] that piano keyboard training would enhance the learning of math and science concepts which use ST reasoning. Furthermore, it was suggested that certain math and science concepts known to be difficult to teach[16] can be learned using ST reasoning methods, especially at an early age. The purpose of this study is to test the hypothesis that ST reasoning methods, in conjunction with piano keyboard training, will enhance the learning of difficult math concepts[16].

ST reasoning and proportional math

A study[17] of 45 countries using 500,000 students has shown that the US is below average in mathematics. Specifically, US students are below average in geometry and proportional reasoning, which will harm their understanding of specific science concepts. These deficiencies carry over to poor performance in college-level math and science.

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Traditionally, proportional math is taught using language–analytic methods with ratios and fractions leading to comparing of ratios or proportional math in fourth through eighth grade. ST methods, of course, play a hands-on role in early childhood learning of math concepts using, for example, blocks. Computer software programs are also useful for introducing ST methods. However, ST reasoning[18,19] is for the most part neglected:

1. Neither approach is carried far enough in depth, in purpose, or in the full use of the young child's ST capabilities.
2. They are dropped out when the child is considered 'ready' to go on to the more appropriate and powerful language–analytic methods.

We contend that these are major flaws in our educational system. Thus some four years ago we set about developing computer software to teach math using ST methods.

We report here the development of a nonverbal, Spatial–Temporal Math Video Game software designed to teach fractions and proportional math, and its dramatically successful use by second-grade children. We also report the development of a corresponding companion software ST Math Video Game Evaluation Program. This Evaluation Program (EP) is designed to evaluate the learning of fractions and proportional math, and replaces the Wechsler tasks as a measure of ST reasoning.

The Wechsler tasks, used in the Preschool Study[15], were from the Wechsler Preschool and Primary Scale of Intelligence-Revised (WPPSI-R)[20], which can be used for children from ages three to seven years. *The Wechsler Intelligence Scale for Children–Third Edition* (WISC-III)[21] can be used for children from six to 16 years. For the Preschool study the Wechsler tasks served as an appropriate pre/post-test evaluation, in particular, the Object Assembly task provided an age-appropriate measure of ST reasoning. However, for this study with older grade school children, the Wechsler scales present some limitations. We have therefore decided to use WISC-III scores as a baseline measurement of ST reasoning, rather than as a pre/post evaluation. Our reasons for using the Wechsler tasks in this capacity, rather than as they were used in the Preschool study, are as follows:

1. Administration of the WPPSI-R or WISC-III spatial tasks requires trained and skilled testers.
2. The tests must be given one-on-one and require 1–2 h per child (including the scoring).
3. A certain proficiency in English is necessary in order for children to understand the test instructions; it is therefore difficult to administer these tasks to non English-speaking populations (unlike the previous version of the WISC, the WISC-III does not have a Spanish version).
4. Because knowledge of English is a factor in test administration, using English language training as a control may confound results from the Wechsler tasks.
5. The basic spatial operations required to master performance of these Wechsler tasks do not include the full range of ST operations, such as symmetry operations, which we believe are enhanced by the piano keyboard training.
6. The Wechsler tasks do not assess the math skills, such as fractions and proportional math, that are particularly relevant to enhanced ST reasoning.

Due to these reasons, when we set about developing the new computer ST software to teach math, we also had in mind developing the ST Math Video Game EP as a replacement for the Wechsler tasks.

Piano keyboard training

The proposed[15] role of piano instruction is to enhance the neural 'hardware' in the cortex for ST reasoning. For our piano lessons, we focused on piano keyboard lessons rather than lessons on other instruments because the keyboard gives a visual–linear representation of the spatial relationships between pitches. This is not true with, for example, string instruments, where pitch is not fixed. It is therefore easier to use the piano to teach important musical concepts such as intervallic relationships, which are spatial in nature. Furthermore, we feel that coupling visual information with aural information might assist the neural pattern development relevant to ST operations. Keyboard instruments are also optimal for our purposes because they are available in electronic form, designed for use in group lessons.

Piano training with ST training

As predicted, children given piano keyboard training along with the ST Math Video Game training scored significantly higher on fractions and proportional math than children given a control training along with the ST Math Video Game. These results were readily measured using the companion Math Video Game EP. This ST approach can be generalized to teach other math and science concepts in a complementary manner to the language–analytic methods, and at a younger age. The potential major scientific and educational uses are discussed. The neural mechanisms involved in reasoning through fractions and proportional math during training on the ST Math Video Game might be investigated in EEG coherence studies[10], along with the added cortical role of music listening priming by Mozart's Sonata K.448[8–10].

MATERIALS AND METHODS

Spatial–Temporal Math Video Game

Based on predictions from the structured trion model of cortex and the results from related behavioral studies, we set out to develop video game software to teach math and science through a spatial–temporal approach. The present study concentrates on fractions and proportional math, which are known to be difficult to teach using standard methods. The software (developed by the second author) is language free. A friendly, cute animal

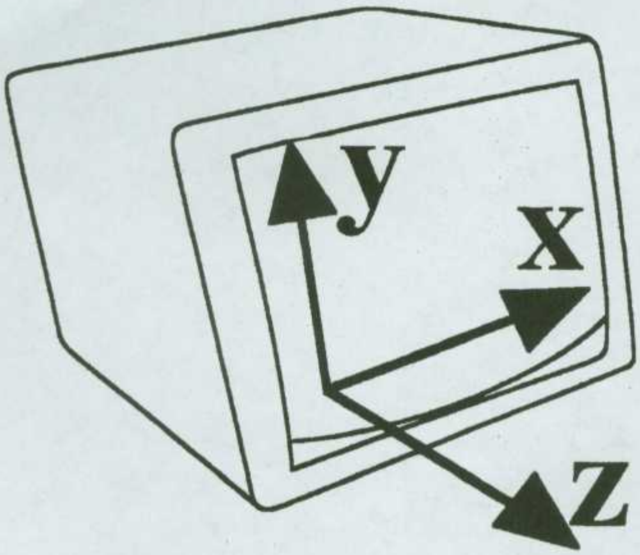

Figure 1: Axis definitions for ST Math Video Game on a computer screen

was chosen as the character of the video game which (racially mixed) boys and girls liked and identified with. The instructions and material are introduced through interactive computer animation, although during training our professional computer instructors did provide introductory remarks and were always present to answer questions. In order to maintain interest, the tasks and settings change throughout the course of the ST Math Video Game. Music is not used, however, sound effects are part of the software.

The ST Math Video Game takes children through two stages. The first stage is a multi-level spatial–temporal training in the form of various games. These games develop skill and confidence in transforming multiple mental images in space and time. For this study, the transformations were limited to (a sequential time series of) the following symmetry operations applied to two dimensional figures (see *Figure 1* for axis definitions): Folding and unfolding around multiple axes in the x–y plane, rotations around the z-axis, 180 degree flips around the x and y axes, and translations in the x–y plane (see *Figure 2A–C* for examples).

The second stage consists of games which challenge children to apply their developed, spatial–temporal skills to solve math and science problems. For this study, we limited the problems to fractions and proportions. Again, this stage is language free and does not require children to perform numerical calculations (see *Figure 2D,E* for examples).

Each level within both stages begins with an introduction. All introductions have the following characteristics:

1. For each question, there is one correct answer out of three or four possible choices.
2. There is no penalty for incorrect responses.
3. Visual feedback is provided which indicates whether or not the child's response is correct, and why the response is correct or incorrect.
4. For each question, children are allowed as many attempts as are necessary before arriving at the correct answer.
5. For each attempt at any given question, the answer choices and the order of choices remain the same.

After the introduction, the game proper begins for each level. Each question consists of one correct answer, taken at random from a set of correct answers for that question, and two to three wrong answers, taken at random from a set of incorrect answers. Thus, two children working independently on the same question could have two different sets of correct/incorrect answers to choose from. This randomization minimized any memory component, and helped maintain children's interest, when replaying the same level. It also prevented children from copying answers from other children.

As in the introductions, visual feedback is given which indicates whether or not the child's response is correct, and why the response is correct or incorrect. However, unlike the introductions, points are given for correct responses, while incorrect or slow responses result in either a reduction in points or a return to the beginning of the level. The ongoing score for each child is displayed in real time, and the final score for each game is recorded in a file for each child.

Pilot study

Subjects

One hundred and two second-grade children from two Orange County schools (IR and SA) were involved in a one-month pilot study to determine the general effectiveness of the ST Math Video Game software. Ages ranged from six years eight months to eight years five months.

School SA is considered to be a below-average demographics school. We took two classes from SA to receive training, and for logistical reasons one class received ST Math Video Game training (Math Group, $n = 20$) while the other class received English language training on the computer (English Group, $n = 20$). Both classes had the same amount of very basic computer lessons at school, approximately once per month, and none of the children had received training similar to our ST Math Video Game software.

A third experimental group (No Lesson Group, $n = 62$) was taken from the above-average demographics school IR.

Training

The purpose of this pilot was:

1. To test the hypothesis that the Math Group would perform better than the English Group or the No Lesson Group on a post-training assessment of ST reasoning.
2. To fine-tune both the first level of the training stage

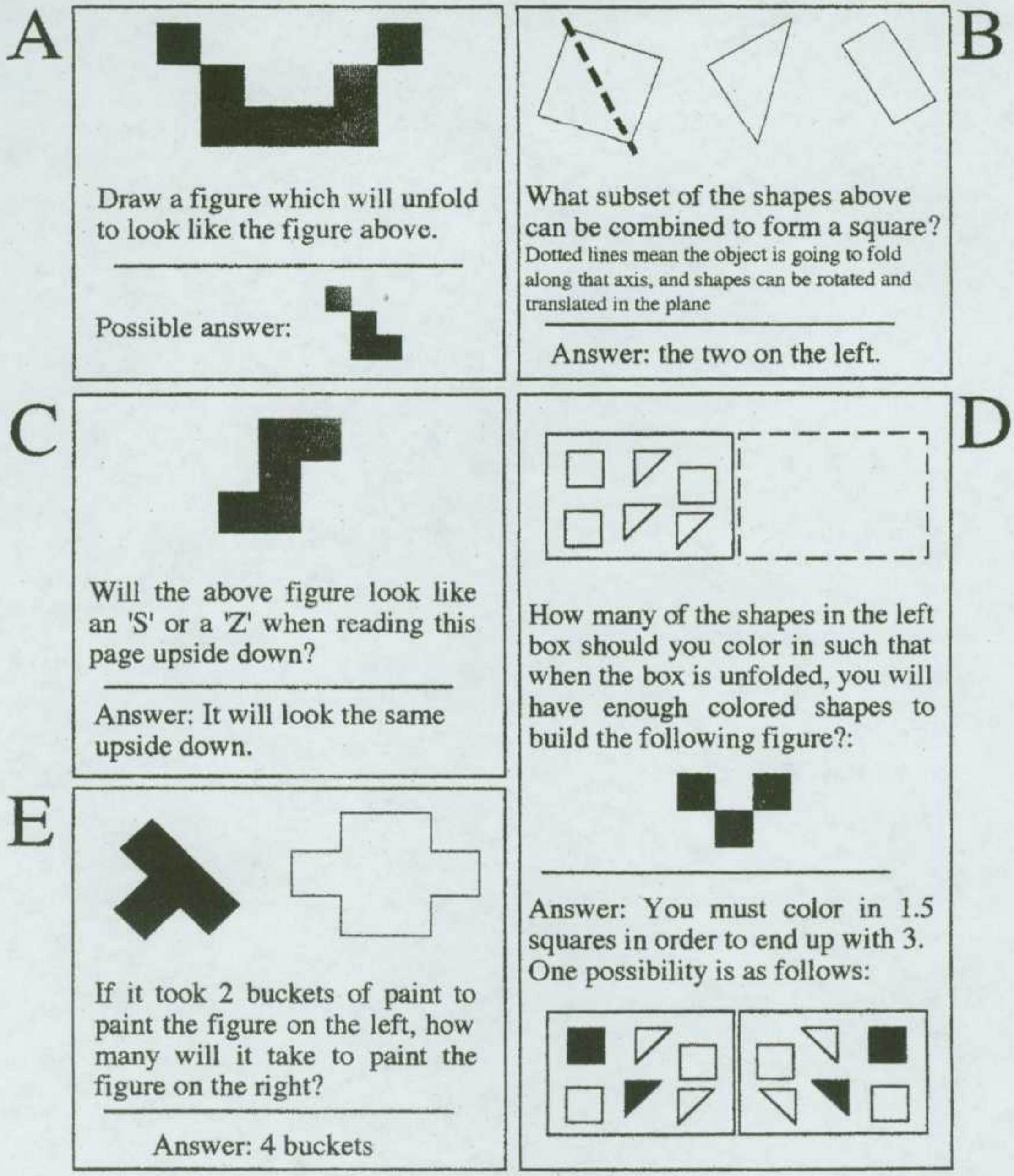

Figure 2: These questions represent the (less difficult) examples of concepts presented in the ST Math Video Game (which does not include the verbal instructions seen here). Children quickly learned what was expected from each question, without instructions. **A** and **C** are training problems; **D** and **E** apply ST reasoning to fractions and proportions

and the proportions level of the applications stage of our Video Game software.

The Math and English Groups from school SA each received training twice a week, in 50-min class sessions for nine sessions. We provided two professional computer instructors who taught both groups. The lessons were given in the school computer lab. There were 14 Mac computers which were adequate to run our ST Math Video Game software. Since there were 20 children in each group, more than half of the children could be sharing a computer at any time.

The Math Group was taught using the first two levels of stage one in the ST Math Video Game software as described above. The English Group was taught using age-appropriate, friendly, commercial software programs designed to teach reading, spelling and writing.

WISC-III assessment

All three experimental groups were tested on their spatial reasoning with three tasks from the Performance sub-test of the *Wechsler Intelligence Scale for Children–Third Edition* (WISC–III)[21]. The WISC–III tasks were used to establish baselines for ST reasoning rather than to measure individual improvements with our one month of training.

Children were tested individually at their schools. The Math and English Groups were tested prior to the start of training. Thirty-four of the 62 No Lesson students were tested. In addition, due to student absences on testing days, 18 of the 20 students in the English Group were tested.

The three tasks used from the WISC–III were Object Assembly, Block Design, and Picture Arrangement. All three involve ST operations, for example, Object Assembly requires the child to assemble pieces of a puzzle to create a meaningful whole. The child must form a mental image of the completed object, then rotate the puzzle pieces to match the image. Performance is facilitated by arranging pieces in particular orders, which defines the spatial–temporal nature of the task. For our analysis we averaged scores from the three tasks, which resulted in a baseline WISC–III score.

Testing procedures followed those recommended by the Wechsler test manual[21]. Test sessions lasted 30–50 min and took place both in the morning and afternoon. Testing was performed by four research assistants; tasks were scored by one assistant. All were blind to both condition assignment and to the hypothesis of the experiment. As specified by the WISC–III scoring instructions[21], raw scores were based on the number of correct responses made within a specified time period, bonus points were awarded for accuracy and speed, and scaled scores were calculated for children at four-month age intervals. The established mean for all WISC–III tests (M) is 10 points, with all standard deviations (σ) equal to 3.

Stanford 9 assessment

The Stanford Achievement Test, ninth edition (Stanford 9) is a nationally calibrated achievement test in reading, writing and math, now used by the entire state of California. The test is administered to students in grades two through 11. We used average math scores on the Stanford 9 from schools SA and IR as baseline measurements to confirm the below-average and above-average achievement of SA and IR respectively, also confirmed by the WISC–III results.

Pilot test assessment

All three experimental groups were given a Pilot assessment test at the end of training for the Math and English Groups. Due to student absences on the day of testing, 19 of the 20 students in the Math Group were tested. All students in the No Lesson and English Groups were tested.

Our Pilot assessment was composed of 25 questions to test the ST concepts and proportional math presented in the Pilot version of our ST Math Video Game. The format of the assessment (*Figures 3 and 4*) was different from that of the Video Game (*Figures 1* and *2*), for example, the animal in the Video Game was not used in the assessment. In addition, while the filling process for proportional math problems in the ST Math Video Game used fuel cells (*Figure 2*), the filling process in the assessment used trucks (*Figure 4*). The details of the assessment problems were different from those in the Video Game, in particular in the last ten questions of the assessment.

The experimenter gave the assessment to an entire 20-student class using color transparencies on an overhead projector. The assessment started with a ten-minute verbal Introduction, in which students interacted with the experimenter while doing sample questions. Sample questions were explicit examples explaining each concept in detail using overlays of transparencies. The test questions were also presented on overhead transparencies. Each child was given a test book which contained a separate answer page for each introductory question and for each of the 25 test questions. Each answer page contained four graphic choices, only one of which was the correct answer, which exactly corresponded to four choices presented on each color transparency.

For all questions, the experimenter instructed students to circle the answer they thought was correct. For the introductory questions the experimenter waited until all students understood which was the correct answer before moving to the next question. For the 25 test questions, children were given 30 sec to answer each question from 1 to 15, and 1 min for each question from 16 to 25. During the test administration an assistant walked around to make sure that the children were following directions during the entire assessment and were on the correct page for each question.

Main study

Subjects

We recruited 170 second-graders from an elementary school in Los Angeles (school LA) to participate in a four-month study designed to explore how piano keyboard training, *versus* an appropriate control, in conjunction with the ST Math Video Game affected students performance in math. Thirty-four students withdrew from the school during the course of the study and were not included in the analyses. The students who withdrew were fairly evenly distributed among the experimental groups. This left 136 children, 67 boys and 69 girls, ranging in age from six years eight months to eight years ten months at the time of pretesting. Seventy-six of the children were of Hispanic origin, 59 were African American, one was Caucasian.

School LA is considered to be a below-average demographics school, as well as below average in academic achievement. In a ranking of Los Angeles' 100 poorest-performing schools, this school ranked 48th[22]. The main experimental groups were drawn from five second-grade classes at school LA. The logistics of school scheduling influenced group assignment: Class 1 received piano keyboard training and the ST Math Video Game training (Piano-ST group) for four months. Class 2 received English language training on the computer and the ST Math Video Game training (English-ST Group) for

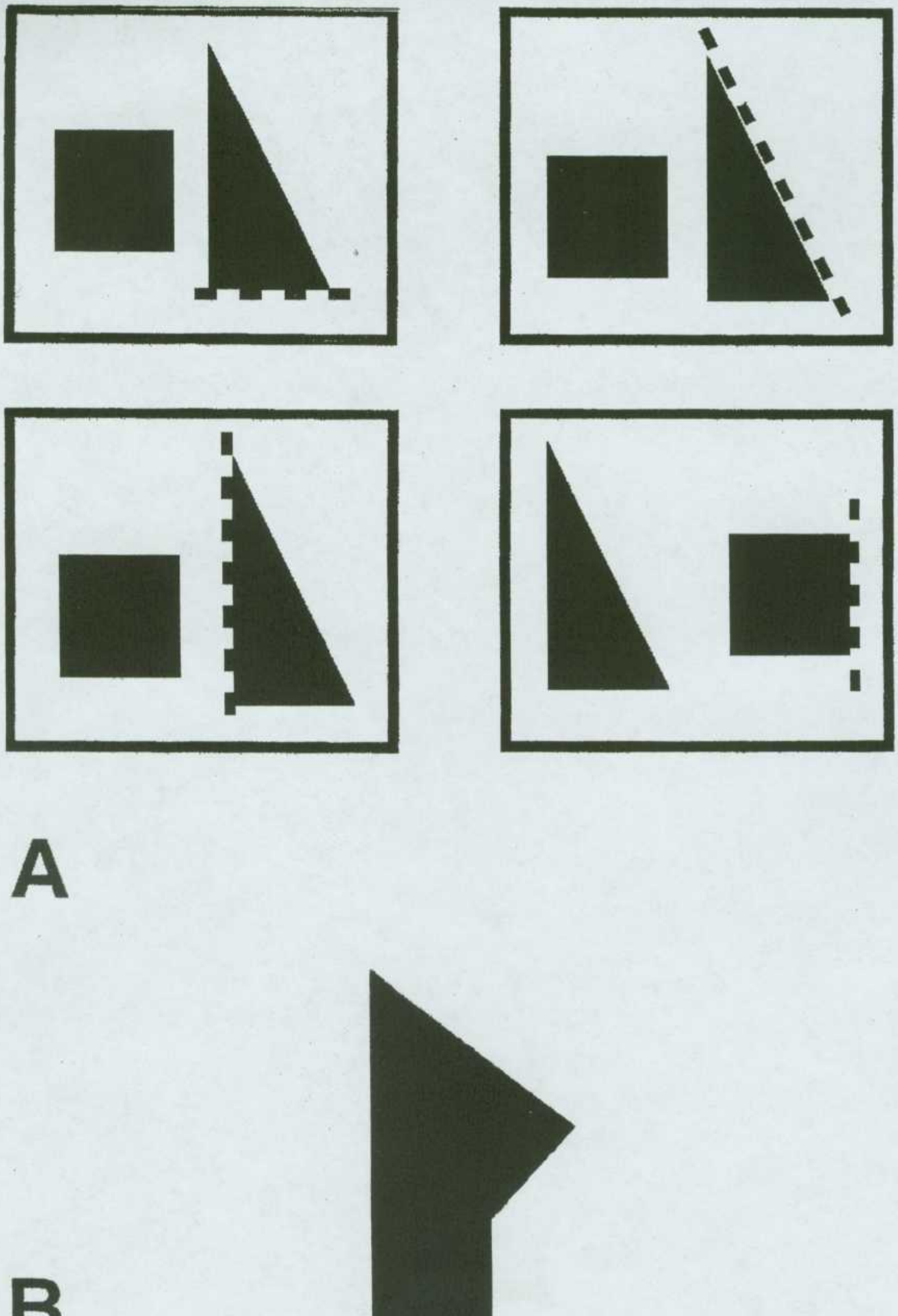

Figure 3: Representative question from the Pilot assessment test. Children had to determine which of four two-shape choices in **A** fit the shape in **B**. In order to determine this, children had to mentally unfold one shape along the axis indicated by the dotted line, then add it to the second shape in the box

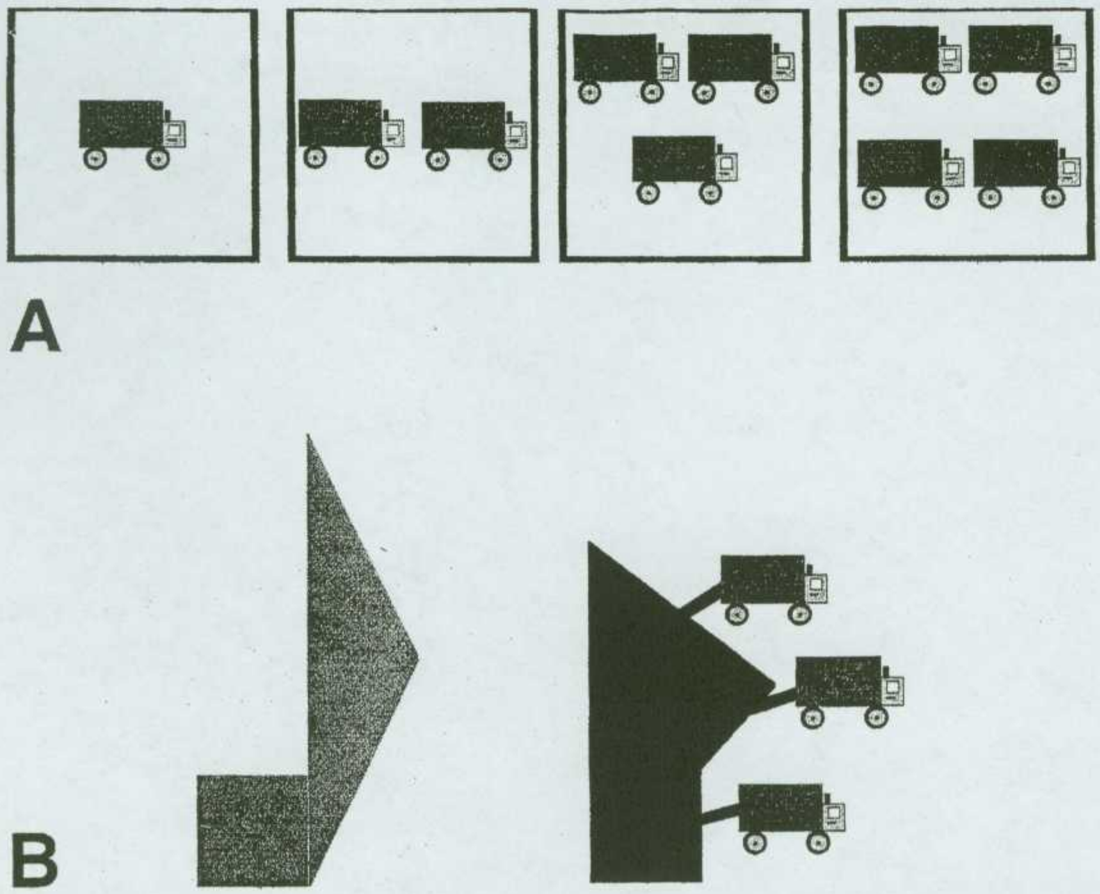

Figure 4: Representative question from the Pilot assessment test. After performing a folding operation (see *Figure 3*) children switched to a filling operation. **B** shows the same shape from *Figure 3B* being filled by three trucks, along with an additional shape. Children chose one of four combinations of trucks from **A** as the correct number of trucks needed to fill the additional shape in **B**. This tests proportional math

four months. Class 3 was randomly and evenly divided between the Piano-ST and English-ST Groups. There were a total of 26 children in the Piano-ST Group and 29 in the English-ST Group. The No Lesson Group ($n=28$) comprised students from classes 4 and 5.

In addition to the main experimental groups, we worked with three groups from classes 6, 7, and 8 which received ST Math Video Game training only, for different amounts of time. The ST-3 Group ($n=17$) received training for three months, the ST-2 Group ($n=20$) received training for two months, and the ST-1 Group ($n=16$) for one month.

None of the children had prior music lessons or computer lessons, and parental involvement was minimal.

Training schedule

All lessons took place at school LA in the same classroom and were conducted in the morning (*Table 1*). The Piano-ST and English-ST Groups each received ST Math Video Game training twice a week in 31 sixty-minute sessions for four months. During the same four-month period, the Piano-ST Group received group piano lessons, and the English-ST Group received group English lessons on the computer, three times a week in 42 sixty-minute sessions.

Due to the logistics of class scheduling, the Piano-ST Group was divided into two sub-groups of 17 and nine children respectively. The English-ST Group was also divided into two sub-groups: Nineteen and ten children respectively. ST Math lessons for the Piano-ST and English-ST Groups were conducted separately with three classes of 19, 16, and 20.

The three ST Groups also received ST Math Video Game training twice a week in 60-min sessions for the following number of months and lessons, also specified in *Table 1*: ST-3, 22 lessons in three months; ST-2, 17 lessons in two months; and ST-1, 7 lessons in one month.

The Piano-ST Group was our main experimental group. The English Language training on computers controlled for the motor and visual coordination provided by the piano keyboard, personal attention, time away from normal classroom activity, and the child's engagement with the activity. The No Lesson

Table 1: Main study training schedule

Group	n	Monday	Tuesday	Wednesday	Thursday	Friday	#ST Math lessons
Piano-ST	26	Piano	ST Math	Piano	ST Math	Piano	31
English-ST	29	English	ST Math	English	ST Math	English	31
No Lesson	28	–	–	–	–	–	–
ST-3	17	–	ST Math	–	ST Math	–	22
ST-2	20	–	ST Math	–	ST Math	–	17
ST-1	16	–	ST Math	–	ST Math	–	7

Main study training schedule showing treatment groups. All ST Math lessons were 60 min in length. There were 42 Piano and English lessons, also 60 min in length.

Group offered a baseline comparison for the ST Math Evaluation Program. The No Lesson Group also controlled for task artifacts on the WISC–III testing. For example, a particular score may improve because the children enjoy it more with age, rather than as a function of treatment.

The three ST groups allowed us to begin evaluating the ST Math training software. We were able to compare performance on the ST Math Video Game EP after four months, three months, two months, and one month of training, and with the performance of the No Lesson Group.

Piano keyboard training

Piano keyboard lessons were designed, supervised and conducted by the first author, with one assistant teacher, a professional piano instructor. We used two Yamaha MLC 16 Laboratory System teacher consoles, each linked to ten Yamaha YPP-15 keyboards. The keyboards were placed on child-size tables, four per table, with the tables arranged in a generally square configuration.

For the purposes of this study, the first author developed an instructional methodology derived from several standard music education systems. Based on results from the priming experiment[9] we predicted that a listening component added to standard piano lessons would further enhance ST reasoning. Thus, each lesson began with 10 min of listening to piano music, which we used in order to be consistent with the instrument being taught. We focused on Mozart piano sonatas because to date experimental data is available only for the effect of Mozart Piano Sonata K.448 on the enhancement of ST reasoning. During piano instruction children were taught basic musical concepts: Finger number associations, clef signs, rhythmic values, identifying letter names on the staff and on the keyboard. They learned to read and play simple melodies for right hand alone (RH), left hand alone (LH), and hands together.

After four months, all children were able to identify treble and bass clefs, count combinations of note values, and read letter names in RH C position from the staff, and identify them on the keyboard. All 26 children were able to play simple melodies for RH and LH, separately and together, in LH F position and RH C position. All 26 were able to count the note values in the melodies they played. Fifteen of the 26 Piano-ST children were also able to read and play RH G position and LH C position after four months.

English language training

English language lessons were conducted by one professional computer instructor. The assistant piano teacher also served as assistant teacher to our computer instructor, since the software used was readily understood and not difficult to teach.

Lessons were conducted on 20 Mac 5400 computers. The computers were placed on child-sized tables, three per table, with the tables arranged along two adjacent walls of the room. Each child worked on a separate computer. Each lesson was conducted by the two teachers with the entire class on computers for the whole 60 min.

Age-appropriate, friendly, commercial software programs designed to teach reading, pronunciation, spelling, and sentence structure were used. After four months, most children were able to spell and pronounce approximately 30 vocabulary words, and to use them in written sentences. Prior to training, on average children were not able to perform these tasks.

ST math training

Training with our ST Math Video Game proceeded as described above. All lessons were conducted by one professional computer instructor on the same 20 Mac 5400 computers used for English language training. Each child worked on a separate computer, except for one level, where two students competed at the same computer.

All 55 children in the Piano-ST and English-ST Groups completed all levels of the ST Math Video Game. However, approximately half the children needed extra help from the instructor to pass the last three levels. The remainder of the students completed the final level with no help or prompting. Our computer instructor estimates that four to six additional lessons would have been sufficient to allow the children who needed help to finish on their own.

All 37 children in the ST-3 and ST-2 Groups completed all levels of the ST Math Video Game. However, their pass criterion was lower than that for the Piano-ST and English-ST Groups. The ST-3 and ST-2 Groups were required to pass levels three, four and five once *versus* three times for Piano-ST and English-ST Groups. ST-3 and ST-2 had only one day with level six, the final level, and were not required to pass it. The ST-1 Group completed level one with the three pass criterion, then were introduced to all remaining levels, except the final one. They were not required to pass any level after the first.

WISC–III assessment

As in the Pilot Study, we used three tasks from the WISC–III as a pretraining baseline of ST reasoning (Object Assembly, Block Design, Picture Arrangement). Children were tested one to two months prior to training. However, in order to obtain additional data, we also retested children with the WISC–III after four months of training and after five to six months had elapsed since pretesting. The No Lesson Group was retested after the same time interval had elapsed between pre- and post-testing.

Seventy-one of the 83 children in the Piano-ST, English-ST, and No Lesson Groups were tested with the WISC–III. The 12 children who were not tested began the program too late to be pretested, due to the five month interval which must elapse between pre- and post-testing. Thirty-four of the 37 children in the ST-3 and ST-2 Groups were tested with the WISC–III; three began the program too late to be tested. The ST-1 Group was not tested with the WISC–III.

Testing procedures followed those recommended by the Wechsler test manual and proceeded as described above. Pretesting was performed by four research assistants, blind to the hypothesis of the experiment, and by the first author. Since group assignments had not yet been made, all were blind to group assignment. Preliminary analysis conducted on data gathered by the research assistants and by the first author showed no differences, so the data were pooled. Post-testing was conducted by three research assistants, blind to both the hypothesis of the experiment and to condition assignment. Scoring and scaling were performed as described above under Pilot Study section.

Spatial–Temporal Math Video Game Evaluation Program

The ST Math Video Game Evaluation Program, or ST Math Video Game EP, is a two-part program. It consists of a one-hour introduction session for children who have not had the ST Math Video Game training, and the testing session itself. One hundred and twenty-seven of the 136 children were tested with the EP testing session; seven of the No Lesson Group and two of the Piano-ST Group were absent on testing days and were not tested. The No Lesson Group, which also received the one-hour introduction session, was retested a second time with the EP one month after taking the test for the first time. For all groups, the EP was administered by our computer instructor, who gave verbal instructions on how to answer each type of question, and was available at all times to address difficulties any student might have.

The ST Math Video Game EP is composed of 44 nonverbal questions of the types shown in *Figure 2*; three questions of type A, 10 of type B, 11 of type C, and 16 of types D and E. Four additional questions deal with other aspects of spatial–temporal symmetry. Each type of question is introduced with a demonstration in which the software gives solutions to two examples of that type. Most questions on the test are multiple choice with four choices, only one of which is correct. However, there are also other formats, such as questions that require students to draw something on the computer, and questions that require students to select the appropriate subset of answer choices that best makes up the solution. After selecting a solution, students are able to change their answer choice before going on to the next question.

The No Lesson Group was given the one-hour introduction session and the EP on two consecutive days. During the introduction, students are taught basic concepts of symmetry and given physical demonstrations of ST operations such as rotation, folding and unfolding. Students are then guided through selected parts of the ST Math Video Game in order to experience interacting with the computer in the ways required of them during the EP.

RESULTS AND DISCUSSION

ST Math Video Game results

The results of the Pilot Study Assessment Test, shown in *Figure 5* and *Table 2*, demonstrate the effectiveness of the ST Math Video Game in teaching the math concepts given in *Figure 2*. The Math Group scored a striking 36% higher than the control English Group. These two groups are from the below-average demographic school SA. The Math Group also scored 14% higher than the No Lesson control group from the above-average demographic school IR. The distribution of the results on each of the 25 Assessment Test questions showed that the English-ST and No Lesson Groups understood the nature of the questions and performed significantly above chance.

The results of the ST Math Video Game EP from the four-month Main Study at (inner-city) school LA, shown in *Figure 6* and *Table 3*, are even more dramatic, and show the benefit of piano training in conjunction with the ST Math Video Game training. The Piano-ST Group scored 15% higher than the control English-ST Group overall on the 44 questions, and a striking 27% better on the 16 questions devoted to fractions and proportional math. Note that the last piano lesson for the Piano-ST Group was given six days before the testing on the Math Video Game EP. Both the Piano-ST and English-ST Groups (which received the ST Math Video Game training) performed over 100% better than the No Lesson Group from the same school. Both training groups performed far above chance level, which is a score of 7.17 out of 44 questions.

Of the 12 students from these three groups (Piano-ST, English-ST, No Lesson) who began the program after it had already started, seven were in the English-ST Group—one began during the first week of training, three during the third week, one during the fourth week, and two during the eighth week. Three of the 12 late-comers were in the No Lesson Group, two in the Piano-ST Group. The mean score for the seven late-comers from the English-ST Group did not significantly differ from the mean for that entire group. Thus, these seven were not a factor in the English-ST Group under-performing as compared to the Piano-ST Group.

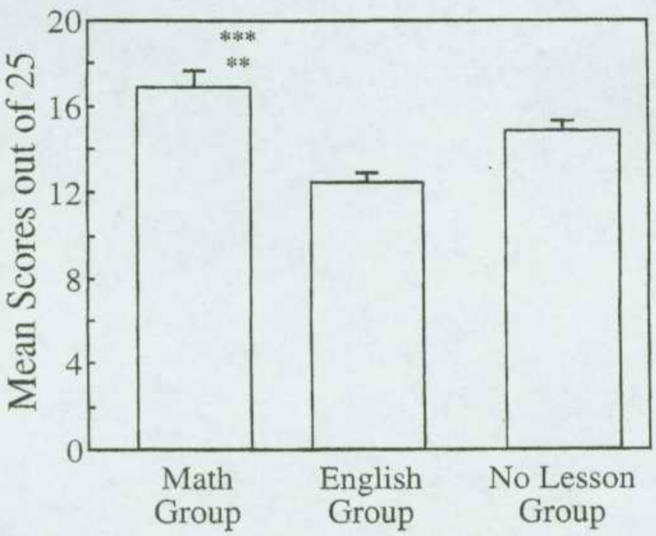

Figure 5: Results of the Pilot assessment test after one month of training with the ST Math Video Game. The Math Group scored 36% higher than the control English Group from the same below-average demographic school, SA. This difference is significant to $p<0.001$ (see *Table 2*). The Math Group also scored 14% higher (significant to $p<0.01$) than the No Lesson control group from the above-average demographic school IR

All six groups, including the three ST groups, show a striking learning curve when results from the ST Math Video Game EP are plotted against number of lessons. The curve rises sharply from the No Lesson Group to ST-1, becomes more shallow between ST-1 and ST-2, and then levels off after ST-2 (*Figure 7*).

Future investigations should include a ST Math only group that has the same amount of training time as the piano training, as well as other controls. Due to available resources and the logistics of class scheduling, we were not able to include such a group (a ST-4 Group). However, based on the leveling off of scores after 17 lessons, as seen in *Figure 7*, we predict that scores on the ST Math Video Game EP for a ST-4 Group would have been similar to scores for the English-ST Group.

WISC–III and Stanford 9 results

Results from the Stanford 9 confirm that school SA is below average in math while school IR is above average. As seen in *Table 2*, second graders from SA ranked in the 27th percentile in math as compared to a nationally selected group, while second graders from IR ranked in the 67th percentile.

Pre-testing with the WISC–III ST tasks was useful in that it verified that children from the below-average demographic schools LA and SA were indeed performing below national norms in ST reasoning. WISC–III pre-testing also verified that children from the above-average demographic school IR were performing above the national norms (*Tables 2* and *3*).

Although we are using WISC–III scores (on the three ST tasks described above) as a baseline comparison rather than as a post-test measure, it is interesting to note that scores for the Piano-ST Group improved approximately 1.5 points on the post-test as compared to the pre-test. Scores for the English-ST Group also increased by approximately the same amount. It is possible that the increase in the English-ST Group's scores was a result of

Table 2: Pilot study results

Group	School	n	Pilot ST assessment	Statistics for group comparisons	WISC–III pre-training	Stanford 9 math score for entire 2nd grade[25] (%)
Math	SA	19	16.89 ± 0.64	(Math–English) $p<0.001$ (Math–No Lesson) $p<0.01$	($n=20$) 9.11 ± 0.44	27
English	SA	20	12.45 ± 0.60	–	($n=18$) 9.18 ± 0.65	27
No Lesson	IR	62	14.84 ± 0.38	(No Lesson–English) $p<0.01$	($n=34$) 10.85 ± 0.48	67

Pilot Assessment scores (see *Figure 5*) are means for each group ± 1 standard error; p values, calculated with a t-test, show the mean score for the Math Group is significantly higher than either the English or No Lesson Group score, and that the No Lesson Group score is significantly higher than that of the English Group. No gender differences were found in the Pilot assessment data. Both WISC–III scores (the average of the three tasks administered) and the Stanford 9 scores demonstrate that school IR out-performs SA in baseline tests of ST reasoning and math. Thus, not only did students from SA taking the ST Math training out-perform the English control group on the Pilot ST assessment, but they also did significantly better than the No Lesson Group from higher-achieving school IR.

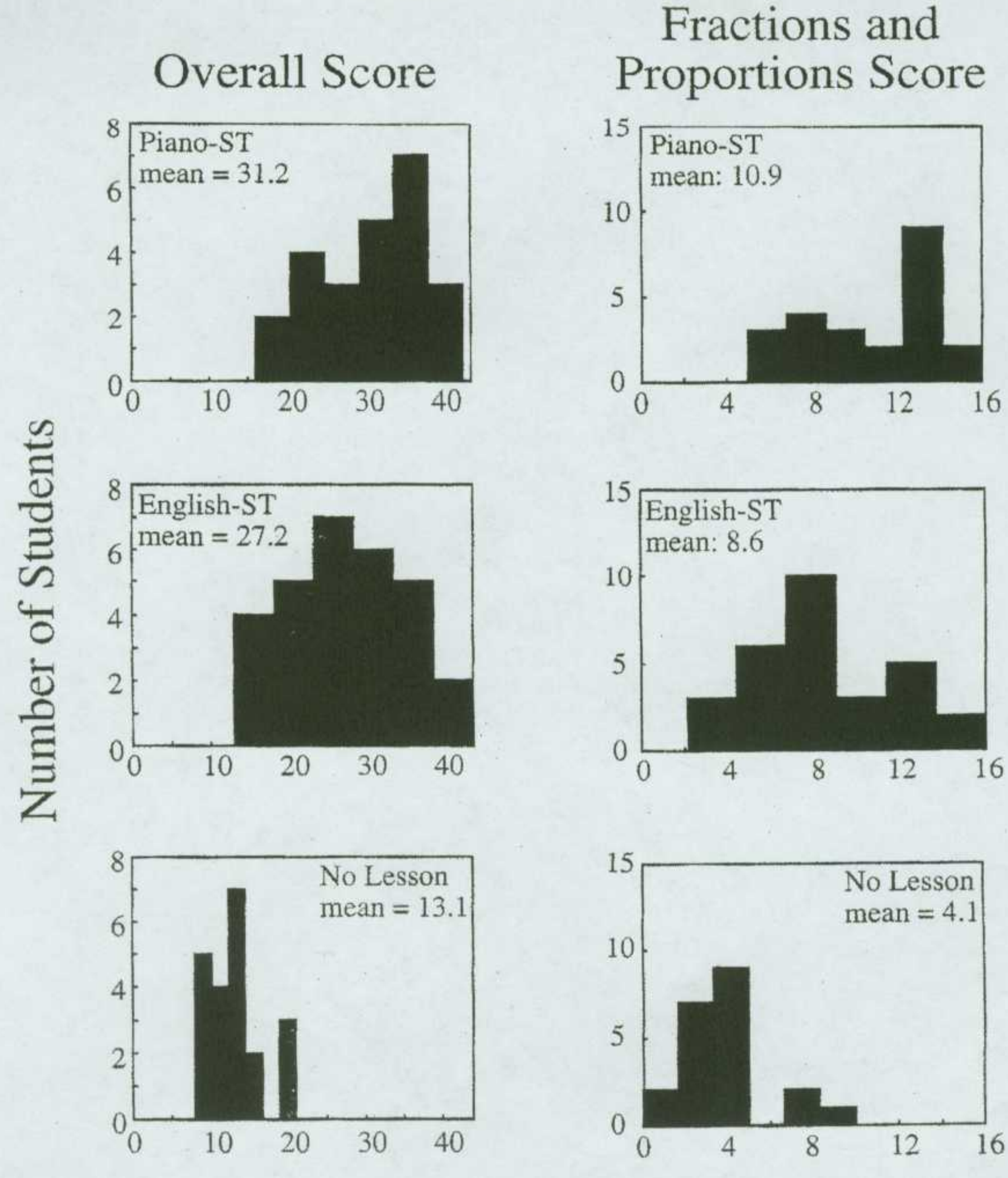

Figure 6: Results of the ST Math Video Game EP from the Main Study (see *Tables 1* and *3*), showing histograms of number of students *versus* score on the EP after four months of training. The left histograms plot scores from the entire EP: The Piano and English groups each scored over 100% higher than the No Lesson Group, and the Piano-ST Group scored 14.7% higher ($p < 0.05$) than the English-ST Group. The right histograms plot scores from the subset of questions on the EP concerned specifically with fractions and proportional math: Again, Piano and English groups each scored over 100% higher than the No Lesson Group and the Piano-ST Group scored a striking 26.7% higher ($p < 0.05$) than the English-ST Group

English training providing better English comprehension and therefore better comprehension of the WISC–III instructions.

However, as expected (see Introduction) these improved scores did not mirror the dramatic 100% better performance in ST reasoning on the ST Math Video Game EP found for the Piano-ST and for the English-ST Groups as compared to the No Lesson Group. In addition, the enhanced performance of the Piano-ST Group, particularly in the area of fractions and proportional math, as compared to the English-ST Group was not measurable by the WISC–III tasks, which are not designed for this purpose. Thus, the WISC–III results are valuable as a baseline measurement of spatial reasoning,

Table 3: Main study results

Group	*n*	EP overall score (out of 44)	EP score, fractions/ proportions (out of 16)	Statistics	WISC–III pre-training
Piano–ST	24	31.21 ± 1.48	10.91 ± 0.71	(Piano–English, overall) $p < 0.05$	8.07 ± 0.50
English–ST	29	27.24 ± 1.50	8.62 ± 0.64	(Piano–English, fractions) $p < 0.05$	8.47 ± 0.44
No Lesson	21	13.14 ± 0.78	4.05 ± 0.50	(Piano–No Lesson, overall and fractions) $p < 0.001$	5.91 ± 0.48
ST–3	17	25.41 ± 1.68	8.35 ± 0.77	–	7.06 ± 0.54
ST-2	20	25.25 ± 1.61	7.88 ± 0.72	–	6.79 ± 0.54
ST-1	16	22.13 ± 1.31	7.01 ± 0.72	–	–

Main study results for school LA showing average score, ± 1 standard error, for each group on all 44 questions on the EP (see *Figures 6* and *7*). Chance performance is a score of 7.17. Also shown are average scores for each group, ± 1 standard error, on the 16 questions focused on fractions and proportional math. WISC–III scores (the average of the three tasks administered) demonstrate that all participants performed below-average on baseline tests of ST reasoning (Stanford 9 results were not yet available at the time this study was completed). These results show the Piano Group performed 14.7% better than the English Group on measures of ST reasoning, and a striking 26.7% better on fractions and proportional math. The Piano and English groups each performed over 100% better than the No Lesson Group.

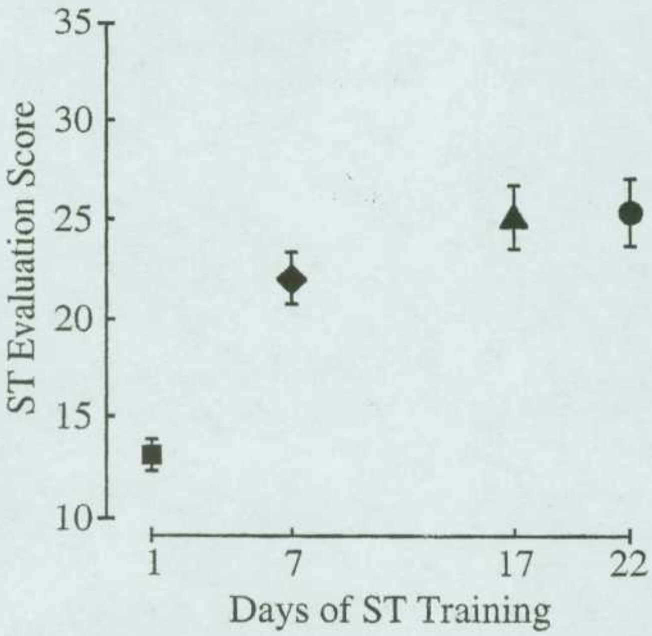

Figure 7: Plot of ST Math Video Game EP *versus* groups having different days of ST training. Each data point represents the average score of a different group (*Table 3*) on the EP. The EP consists of the test plus one day (1 h lesson) of ST training for those children who had no previous ST training. Thus the No Lesson Group (square) had one day of ST training. Group ST-1 (diamond) had 7 days of ST training, group ST-2 (triangle) had 17 days of ST training and group ST-3 (circle) had 22 days of ST training. The rapid rise in performance level *versus* days of training suggests the ST Math Video Game is tapping into fundamental cortical processes of ST reasoning. Chance performance was a score 7.17

rather than as a measure of individual improvement after training. Future evaluations of enrichment programs with regard to their success in giving improved understanding of math concepts could be done with pre- and post-assessments using the ST Math Video Game EP specifically designed to test this.

Qualitative issues

In addition to these quantitative results, interviews with the homeroom teachers showed qualitative improvements in several relevant academic areas. The teacher of the Math Group at school SA during the Pilot Study reported that four of five significantly below-average students caught up and understood numbers better after the month of training. Teachers of the Piano-ST Group in the Main Study at school LA reported better attention and concentration abilities in almost all the piano students. Perhaps the most interesting qualitative observation was how few lessons were necessary for these below-average second graders to master the sophisticated spatial–temporal reasoning tasks in the Math Video Game software.

An important educational question is whether or not time spent at piano and ST Math lessons interfered with normal classroom instruction. Interviews with teachers at school LA show that the additional instruction did not distract or take away from classroom time. Instead, it facilitated a more carefully planned curriculum and more effective time management. Teachers were able to cover all normal subjects and lessons and still have time for piano and ST Math.

Future investigations

We have shown here that ST methods in the nonverbal Math Video Game allow children to learn fractions and proportional math. In particular, children from disadvantaged backgrounds learned these concepts at an earlier age than normally done in the public schools. This is significant given the fact that these concepts are known to be difficult to teach using standard language–analytic methods. In addition, the results presented here indicate that piano keyboard training, in conjunction with ST training, further enhances the learning of fractions and proportional math. The next step is to demonstrate that these conceptual understandings can lead to better performance on language–analytic assessments, such as standard math word problems.

An important question to ask is why piano lessons may have helped the learning of fractions and proportional math. Previous research indicates that piano lessons[15] specifically enhance ST reasoning. Since proportional thinking relies on ST reasoning, it follows that piano lessons, through an enhancement of ST reasoning, may lead to better fraction and proportional-math thinking skills. The learning of music emphasizes thinking in space and time. We have already discussed why piano lessons, in particular, emphasize the spatial dimensions of music: With the keyboard, students have a clear visual representation of auditory space (unlike pitch representation on many other instruments).

Other reasons why music in general may enhance ST reasoning and proportional math are as follows:

1. When children learn intervallic relationships (the distance between two notes) they are learning spatial relationships.
2. When children learn rhythm, they are learning ratios, fractions, and proportions—an eighth note is half of a quarter note, which is half of a half note, which is half of a whole note; an eighth note is to a quarter note as a half note is to a whole note, etc.
3. Playing an instrument has a temporal element; children learn to think ahead. For example, a child will need to be playing one note while at the same time looking at the next note on the page and determining where to place his/her fingers. Ultimately, students learn to look ahead in the written music for whole patterns of notes—ascending, descending, repetitive, even symmetrical patterns. They learn to determine what they will play next, before they start playing it.
4. Music listening also has a temporal element. When children are familiar with a piece, they can think ahead and anticipate what they will hear next.

The performing of music exercises ST reasoning and proportional thinking using auditory, visual, and sensory–motor modalities. We suggest that piano keyboard lessons in combination with the ST Math Video Game, which specifically teaches proportional math through the visual mode, can be a powerful educational tool.

The ST methods in the Math Video Game software can be extended to almost all math at all levels. As an example, the use of symmetries in ST methods has been used successfully by Xiaodan Leng (private communication) in a college level precalculus course analyzing behavior of equations. Thus, the use of spatial–temporal methods to enhance understanding of math is not limited to disadvantaged and/or very young students.

In addition to the teaching of math, we expect these ST methods can be successfully extended to teaching all branches of science, since most scientists and mathematicians[18,23] rely heavily on this ST faculty. In fact, Albert Einstein made many references to his dependence on ST reasoning—in a letter to a friend he wrote[23]:

> *'The words or the language, as they are written and spoken, do not seem to play any role in my* mechanism of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be voluntarily reproduced and combined . . . Conventional words or other signs have to be sought for laboriously in a secondary stage . . .'

And Richard Feynman, perhaps the most important and influential physicist of the second half of this century, described the relationship between ST and analytic reasoning as follows[24]:

> '. . . it's a crazy mixture of partially solved equations and some kind of visual picture of what the equation is saying is happening . . . Strange! I don't understand how it is that we can write mathematical expressions and calculate what the thing is going to do without being able to picture it.'

However, despite its prevalence in the pursuit of science, ST reasoning is almost completely absent from our current educational system.

As noted above, the most interesting qualitative observation was how quickly the children mastered the sophisticated ST reasoning tasks in the ST Math Video Game software. For example, all children in both Piano-ST and English-ST Groups passed the first level of stage one before the fourth lesson. In order to pass, each child was required to achieve 320 points on each of three different trials of level one (each child had four to six trials of level one per lesson). This can be compared to the performance of a dozen university science researchers, the majority of whom did not achieve more than 200 points on either of two trials.

We suggest that this gives considerable support to the strong predictions of the trion model[5]:

1. That the elemental operations inherent in the cortex are the symmetry operations.
2. That they form the basis for higher brain functions of ST reasoning.

If this trion model prediction was incorrect, we would expect that the time necessary for second graders to master the sequences would be much longer. This suggests that a study to quantitatively determine the time to achieve a successful criterion on a level of the Math Video Game, *versus* that of an appropriate control, would be of large neuroscientific interest.

The long-term enhancement (lasting at least six days after the final piano lesson) of performance for the Piano-ST Group over that of the English-ST Group in fractions and proportional math suggests a neurophysiological experiment: In analogy to the EEG coherence study of the Mozart Effect[10] we suggest that possible priming through listening to Mozart's Piano Sonata K.448 just prior to training with the Math Video Game be investigated in EEG coherence studies.

Another area that should be investigated is how different methods of music instruction appropriate for group settings (such as the Suzuki, Dalcroze, Orff, *Kodaly, etc. methods) affect ST reasoning and math performance. Some of these methods may work better* than others for specifically enhancing ST reasoning, and/ or may work more efficiently in a public-school setting.

It is interesting to note that a general trend can be observed in the Stanford 9 results for below-average schools in Orange County, CA, USA[25]: Math scores that are below average at second grade tend to decrease as grade level increases. This may be due to the fact that the Stanford 9 does not test for fractions and proportional math on the second-grade level, but does so for higher grades (as children begin to learn these more difficult math concepts their performance seems to decrease). Thus the Stanford 9 math test for higher grades can serve as an appropriate standardized evaluation of achievement in fractions and proportional math as taught by the Math Video Game.

We propose that a large standardized study, involving perhaps 20 schools nationwide, be done to investigate enhanced performance in math concepts due to a combination of piano keyboard training with spatial–temporal training. Measurements of ST reasoning, proportional math, and general math achievement can be obtained from the ST Math Video Game EP and from the Stanford 9.

In order to test whether or not a program combining piano keyboard and ST training can be integrated into the regular school curriculum, a long-term educational experiment of two to three years is necessary. We predict that the large magnitude of the enhanced math performance reported in this study would increase even further with the two to three years of training *versus* the four months given here. Success of this implementation study would revolutionize the learning of math and science by all children.

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