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IMPACT OF WEB-BASED 4D VISUALIZATION IN CONSTRUCTION SCHEDULING

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ABSTRACT

Four-dimensional CAD (4D CAD) is being utilized in the construction industry to improve collaborative decision-making in construction scheduling. Recent research has developed a Web-based 4D visualization application in order to distribute the 4D model over the Internet. This application creates 4D visualization of the updated construction schedule automatically on the Web browser and allows users to navigate around the 4D model.

In this paper, an experiment to test whether Web-based 4D visualization would help professionals understand the construction schedule and improve communication among team members is presented. For the experiment, an Internet role-playing game was developed to measure how fast or how effectively the players can detect the logic errors hidden in the construction schedule and communicate with each other using the Web-based 4D model. The results of the experiment showed that the teams that used Web-based 4D visualization detected more logic errors more effectively than the team that used the 2D drawings on the Web browser.

KEYWORDS

Web-based 4D Visualization, Web-based Project Management, 4D CAD, Construction Scheduling

1. INTRODUCTION

Construction planning has to do with breaking the project into identifiable elements and building a logical network among these elements. In order to develop a construction schedule, the scheduler first interprets the given information to determine what to build. The scheduler then identifies activities and develops their sequence relations. Finally, the scheduler determines when activities will take place by calculating activity and project durations (Fischer and Aalami, 1995). Current scheduling practice abstracts these processes and illustrates them using a Gantt chart or Critical Path Method (CPM) network (McKinney, et al. 1996). The conceptual expression of the schedule is effective to illustrate the entire construction schedule at a glance. However, it takes many years to become an experienced scheduler and it is often a challenge to develop realistic and practical schedules using conceptual expression (Fischer and Aalami, 1995). Even experienced scheduler could create some logical errors in developing the construction schedule. Logical errors in construction scheduling are improper sequence relations among the work packages.

Currently, in order to identify logical errors within the construction schedule, the constructors read two-dimensional (2D) drawings, visualize the structure in their mind, and then link that visualization with the schedule information provided by the bar chart or the CPM network (Koo and Fischer, 1998). Experienced constructors can interpret the construction schedules without difficulty using the 2D drawings and the bar chart, and react effectively to logical errors. However, novice constructors or owners, who do not necessarily have knowledge of construction, may not be able to integrate the bar chart and the 2D drawings to visualize the construction schedule intuitively. Therefore, they may never notice errors in scheduling sequence. The increasing complexity of the constructed product, combined with intense project schedule pressure, has created the need for more sophisticated tools to help project participants plan and manage their projects more effectively (Williams, 1996). Project participants want comprehensive tools to simulate and visualize construction sequences as part of an interactive experience (McKinney, et al. 1996)

Recent research developed a new way of representing the construction schedule using three-dimensional (3D) computer model (Simons, Thornberry, and Wickard, 1988; Collier and Fischer, 1995; Vaugn 1996; Williams 1996). Bechtel developed Construction CAE that integrates 3D Computer Aided Design (CAD) models with scheduling packages to simulate the construction operations (Simons, Thornberry, and Wickard 1988; Mahoney, Tatum, and Kishi 1990). The Center for Integrated Facility Engineering (CIFE) at Stanford University connected 3D CAD objects with the construction schedule to show the construction sequence visually in 3D CAD environment (Collier and Fischer 1995). It is now being called four-dimensional (4D) CAD. Bechtel also developed 4D-Planner, a graphical simulation tool that helps project managers, construction planners, and field engineers plan and manage their projects effectively (Williams, 1996). These new developments have been applied to actual construction projects that include the San Mateo County Rehabilitation Center campus expansion project (Collier and Fischer ,1996) and a new Walt Disney Concert Hall designed by Frank O. Gehry, who is famous for radical, flowing-curve buildings (Goldstein, 2001).

More recent research developed a tool to distribute 4D visualization over the Internet. Kang (2001) of Texas A&M University developed Web-based 4D visualization software. With this software, users can update the construction schedule over the Internet and the 4D visualization model of the updated construction schedule can be displayed immediately on the Web browser. This research also developed a Web-based experiment tool to measure the impact of Web-based 4D visualization on detecting logical errors in the construction schedule, and conducted an experiment with students studying construction management. This paper presents the implementation and results of this experiment.

2. VISUALIZATION FOR BUILDING DESIGN

Visualization plays an important role in human's cognitive process. Human beings obtain 83% of their knowledge from visual observation (Murgio, 1969). Visual information from which human beings obtain knowledge is described by either text or pictures (Kozma, 1991). Although text is a more advanced way to express an abstract knowledge, pictures have their own value in describing tangible objects. Johnson-Laird et al. (1972) verified from experiment that the use of realistic materials improves performance in a deceptive reasoning problem. Pressley (1977) asserted that "Imposed pictures are almost always learned better than words".

Two-Dimensional (2D) drawings are the most popular means used in the architecture, engineering and construction (AEC) industry to describe designer's idea to the project participants. However, in order to visualize the shape of the structure in 3D world, one has to read several drawings to comprehend the spatial and volumetric aspects of the objects. This process requires education in the conventions of drawing and practical experience. Developing a construction schedule is even harder because one must build a structure step-by-step in one's mind after visualizing it. Therefore, the designer's intention is sometimes misinterpreted.

Three-Dimensional (3D) objects can best be described by 3D visualization (Tufte, 1990). Architects developed a number of specialized methods for presenting their designs such as a 3D miniature model (Giovannini, 1994). Through the 3D miniature model, customers understand the architects' intention more easily. In power plant design, engineers build a 3D miniature plastic model of the structures to detect any possible interference of the components, so that they can save construction cost and time.

As 3D CAD technology became available in the AEC industry, architects realized that a 3D CAD model takes less space, and can be easily distributed. Using 3D CAD, architects were able to build and change a 3D model quickly and more easily. Engineering, procurement and construction (EPC) firms were leaders in the development and implementation of 3D CAD to support their design and construction efforts. Bechtel Corporation's 3D modeling system for plant design (3DM), and Stone & Webster's Construction Management Display System (CPMANDS), Fluor Daniel's CALMA Plant Design System (PDS), and Black & Veatch's POWERTRAK are some of examples of implementing 3D CAD models in design efforts. These firms saw the potential of using 3D CAD for reviewing constructibility, checking interference, materials take-off, and conveying design intent (Mahoney, Tatum, and Kishi 1990).

3. 4D VISUALIZATION FOR CONSTRUCTION SCHEDULING

Recent research has attempted to show the sequence of construction using 3D computer model. Bechtel Corporation expanded use of their 3DM further with the development of Construction CAE to simulate the construction operations and assembly sequence (Simons, Thornberry, and Wickard, 1988). The system includes construction equipment models and allows the planner to include temporary structures or facilities to accurately simulate the construction environment. It also provides dynamic interference checking to validate proposed construction flows and equipment selections (Mahoney, Tatum, and Kishi, 1990). Bechtel Corporation also developed 4D-Planner that is a graphical simulation tool that helps project managers, construction planners, and field engineers plan and manage their projects effectively (Williams, 1996). 4D-Planner allows the user to electronically relate the 3D CAD model and the project schedule. 4D-Planner imports the 3D CAD model from MicroStation, Plant Design System (PDS), and AutoCAD using Walkthru file format. 4D-Planner also imports the Primavera file for the project schedule. After the CAD model and the schedule files are imported into 4D-Planner, they can be merged into a simulation file that can be reviewed interactively. When a simulation file is played back, the various components or groups of components are turned on in the model at the appropriate time (Williams, 1996).

In research conducted at the Center for Integrated Facility Engineering (CIFE) at Stanford University, 3D CAD objects were connected with the construction schedule to develop a representation that shows the construction sequence visually (Collier and Fischer, 1995). CIFE and Dillingham Construction demonstrated in the San Mateo County Rehabilitation Center campus expansion project that the 4D CAD was a valuable tool to help people understand a construction schedule intuitively (Collier and Fischer, 1996). Development of the construction schedule in that project was particularly challenging because hospital operations should be uninterrupted during the construction period. The project team combined the construction schedule with 3D CAD model, recorded a visual sequence of construction on videotape, and showed it to the doctors and nurses. The project team found the video presentation was an effective way of disseminating information in the computer to wider audiences. Even people with minimal previous involvement were able to view the animation and quickly understand the impact of planned construction on their department, office, and daily operations (Collier and Fischer, 1996). Walt Disney Imagineering Research and Development and CIFE utilize a 4D CAD model to better understand the construction sequence of a new Walt Disney Concert Hall designed by Frank O. Gehry (Goldstein, 2001). On a structure as complex as a Frank Gehry's Concert Hall, it is virtually impossible for anyone, even an experienced superintendent or scheduler, to visualize the entire project, much less anticipate potential conflicts before they arise. Using Imagineering 4D tools, the project team was able to visualize several what-if scenarios to detect conflicts before the project began. The 4D model helped discover several coordination conflicts on the project. The 4D models also helped subcontractors comprehend access issues. Since the construction site is in downtown LA and streets must remain open, lay-down areas were modeled to ensure efficient and unfettered access paths. Another obvious use for a visualization tool is to inform stakeholders of the approach to construction. Since most board members were unfamiliar with the specifics of the construction process, the 4D presentation helped them understand the special challenges of the site and why certain choices were made (Goldstein, 2001).

However, some limitations of 4D CAD were revealed while using 4D CAD in the construction project. Those are the necessity of large initial investment of time and effort to create a 3D model, and limitations in updating the 4D CAD model (McKinney, et al. 1996). Even though 4D CAD appears effective in supporting the collaborative decision-making process, the multiple steps required to modify the model and distribute it may reduce its desirability in typical projects.

In recent research, Kang (2001) developed a prototype of Web-based 4D visualization software. A software prototype implementing 4D CAD in a Web environment overcomes limitations of current 4D CAD tools. This software permits editing of the construction schedule over the Internet and shows the revised construction sequence visually on a Web browser using 3D computer graphics. This software is composed of a database on a server, Active Server Pages (ASP) scripts, and a Java applet that was developed using Java 3D Application Programming Interface (API) and Java JDBC. The Java applet retrieves the 4D model at the appropriate level of completion over the Internet and allows users to navigate around the model on the Web browser. Web4D visualization software is expected to help professionals expedite the schedule updating process by involving designers and constructors in collaborative decision-making.

4. EXPERIMENT DESIGN

The impact of Web-based 4D visualization was mainly investigated through comparison of the level of collaboration between two groups that use different graphic representations to detect logical errors in the construction schedule.
For this investigation, the experiment was designed to form teams of two participants, who played either an owner's role or a contractor's role, and detected logical errors hidden in the construction schedule collaboratively. The owner's role is to detect logical errors in the given construction schedule and obtain the contractor's agreement for the detection. The contractor's role is to check if the owner can provide a clear explanation about logical errors before acknowledging the owner's claim.

The teams were then randomly divided into two groups, group A and group B, which used different graphic representations for the experiment. One group used a 2D drawing describing the plans and elevations of the structure, and a bar chart showing the construction schedule; while the other group used a 4D visualization showing the construction sequence, and a bar chart.

The experiment participants for this research were undergraduate and graduate students working in the areas of architecture, construction, and civil engineering at Texas A&M University. In order to promote students' participation, an instructor provided extra credit to the students.

The experiment was conducted using the Internet. All instructions and necessary graphic representations were provided to the experiment participants on the Web browser. 4D visualization was provided through the ASP Web page that simulates the Web4D Java applet developed in recent research (Kang, 2001). In Web page, users can navigate around the structure and move back and forth on the construction schedule by clicking buttons provided.

The participants accessed the Web site for the experiment at separate places and communicated with each other using Web-based chat program. The instant chatting facility recorded every conversation made between the team members with a time stamp. Their conversations were recorded automatically in the database with a time stamp. The communication logs were then reviewed to collect the following four types of data:

- Number of logical errors detected
- Accuracy rate in claiming logical errors
- Average elapsed time to detect one logical error
- Average frequency of communication to acknowledge one actual logical error

The above measurements were utilized to determine the level of collaboration of the team for identifying logical errors in the given schedule. The expectation was that differences between the groups would be significant. A further prediction was that the 4D visualization on the Web would produce a greater detection, more accuracy, less elapsed time to detect errors, and require less frequency of communication.

The experiment was designed to investigate the difference of the performance between two identical human subjects due to different graphic representations. It is not easy to assure the reliability of the between-subject experiment because of the huge individual differences between the participants (Nielson, 1993). Team A that uses 4D visualization could finish the given task faster than team B that uses 2D drawings simply because team A is more experienced in using the given resources than team B. If the experiment was repeated with different teams, the result could easily be the opposite. Therefore, the experiment made use of a within-subject design to control individual variability. The experiment was designed to have every team to use both graphic representations for problem solving. To reduce the learning effect in using graphic representations, the teams in group A use 4D visualization for even problems and the 2D drawing for odd problems. The teams in group B uses the opposite resources for the same problems. Table 1 shows the type of graphic representations used in the experiment by each group of teams. In addition to this, the role of the participants in each team is switched after solving the first two problems. Table 2 shows the role of the participants in the team. The alternation between the 2D drawings and 4D visualization in the same group, and the alternation between the owner and the contractor is expected to control for individual variability because all participants play all roles and use both graphic representations. Participants who are particularly talented or untalented should not skew the results, as they affect both sets of statistics equally.

Table 1: Type of Graphic Representations Used in the Experiment

Group	Task 1	Task 2	Task 3	Task 4
Group A	2D	4D	2D	4D
Group B	4D	2D	4D	2D

Table 2: Role of the Participants in the Team for the Experiment

Team member	Task 1	Task 2	Task 3	Task 4
Member A	Owner	Owner	Contractor	Contractor
Member B	Contractor	Contractor	Owner	Owner

The teams in each group were given two training exercises and four tasks. For the two training exercises, the schedules to build a tower using five wooden toy blocks were used. Some assumptions used in building the towers were: 1) no adhesive is used to put two blocks together; and 2) the wooden blocks should be placed one-by-one using only one hand. The tasks used for the first two main tasks were similar to those of the two exercises but more complicated. The wooden toy block towers used in the first two tasks are illustrated in Figure 1 and 2. Three logical errors were created for each task by making some blocks to be unsupported in the building process.

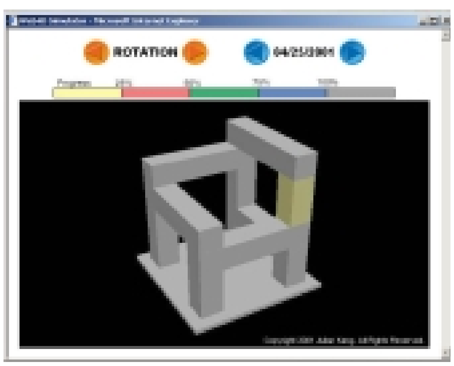

Figure 1: Wooden Toy Tower Model used in Task 1

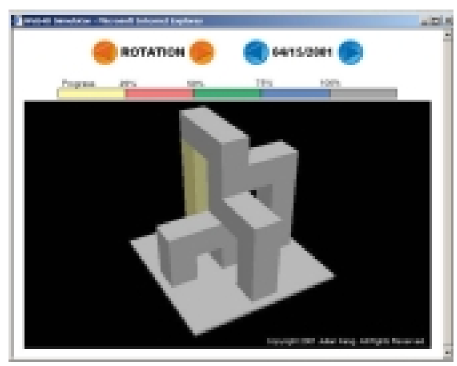

Figure 2: Wooden Toy Tower Model used in Task 2

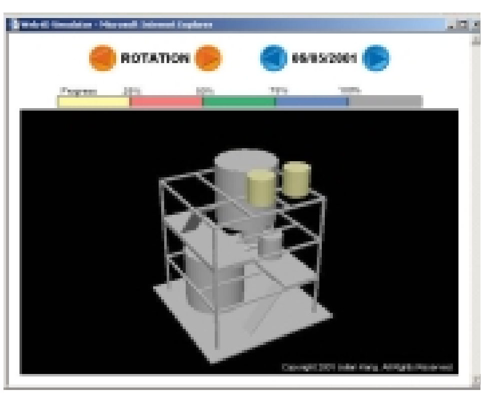

Figure 3: Plant Model used in Task 3

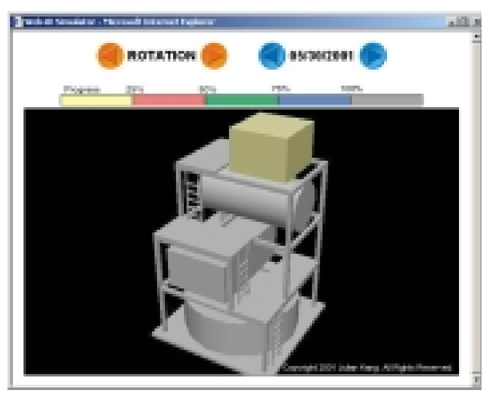

Figure 4: Plant Model used in Task 4

For the third and fourth tasks, the schedules to build small four-story chemical facilities illustrated in Figure 3 and 4 were used. Participants were informed that cranes should hold equipment such as tanks until it was completely installed. Five logical errors were created for each task by violating structural stability or by using restrictions due to crane utilization. For creating logical errors, stairs, beams, plates, and tanks were scheduled to be placed without appropriate supports, or the tanks were placed later than the beams or plates that were supposed to be placed on top of those tanks. According to assumption, any components that were supposed to be placed on top of the tank should be placed after the tank was installed completely. The teams were then asked to detect as many logical errors as possible within 30 minutes for each schedule.

5. EXPERIMENT RESULTS

A total of 84 students formed 42 teams of two to participate in the experiment. Among 42 teams 35 teams finished the experiment as per the instructions. The teams belonged to either group A or group B randomly. Table 3 shows the number of teams in each group and the type of resources they used in the experiment. For the analysis, the measurements are reorganized by the type of graphic representation that the experiment participants used: a 2D group and 4D group. Table 4 shows the number of measurements in each task based on the new arrangement.

Table 3: Number of Teams in Each Group and Type of Graphic Representation Used

Group	No. of Teams	Graphic Representation			
		Task 1	Task 2	Task 3	Task 4
Group A	17	2D	4D	2D	4D
Group B	18	4D	2D	4D	2D

Table 4: Number of Measurements in Each Task

Group	Number of measurements			
	Task 1	Task 2	Task 3	Task 4
2D Group	17	18	17	18
4D Group	18	17	18	17

In the experiment, all conversational exchanges by the participants were saved in the database with a timestamp. Five raw experiment measurements were collected in each task by reviewing the conversation logs:

- Time that the owner started the task
- Time that the owner finished the task
- Number of logical errors that the owner claimed in the task
- Number of actual logical errors that the owner detected in the task
- Frequency of communication in the task

The raw measurements were collected based on the owner's performances. However, these measurements are not results of a single person but represent the results of a team. These are results of team collaboration because the owner's accomplishments in the experiment were affected by the contractor's responses. No owner could claim any logical errors without obtaining the contractor's agreement. The owner spent time in the experiment not only to detect logical errors hidden in the schedule but also to communicate with the contractor to obtain the contractor's agreement. The raw measurements were used to generate the following data in each task:

- Number of logical errors detected
  (= Number of actual logical errors that the owner detected in the task)
- Accuracy rate in claiming logical errors
  (= Number of logical errors that the owner claimed in the task / Number of actual logical errors that the owner detected in the task)
- Average elapsed time to detect one logical error
  (= (Time that the owner finished the task – Time that the owner started the task) / Number of actual logical errors that the owner detected in the task)

- Average frequency of communication to acknowledge one actual logical error
(= Frequency of communication in the task / Number of actual logical errors that the owner detected in the task)

Figures 5, 6, 7, and 8 show the data generated by the above equations.

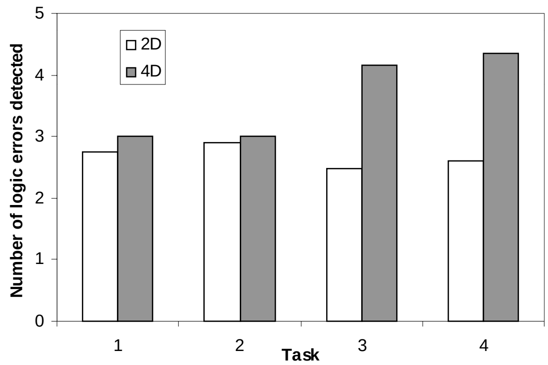

Figure 5: Number of Logical Errors Detected

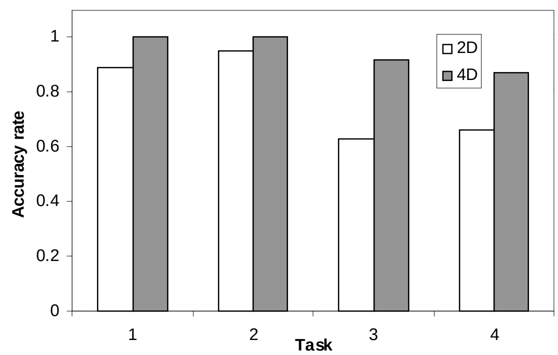

Figure 6: Accuracy rate in Claiming the Logical Errors

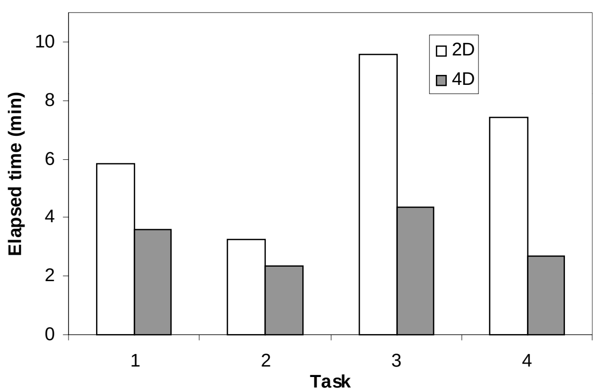

Figure 7: Average Elapsed Time to Detect One Logical Error

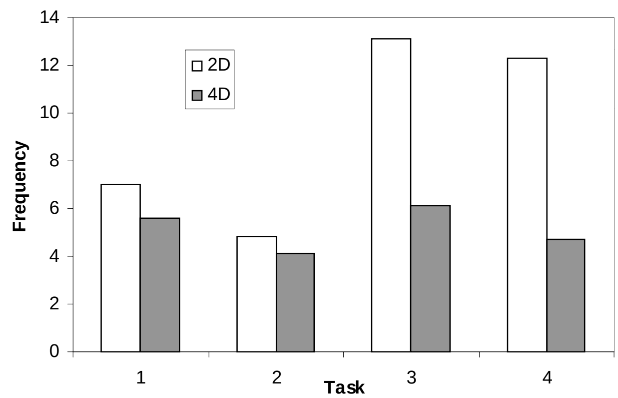

Figure 8: Communication Frequency to Obtain the Contractor's Acknowledgement er logical Error

The results illustrated in Figure 5 show that the 4D group detected more logical errors than the 2D group in task 3 and 4. The statistical test between two groups shows that there is less than 5% chance in task 1, 3, and 4 that 2D group detects equal or more logical errors than the 4D group. In the second task, there is an 8.3% chance that the 2D group detects equal or more logical errors than the 4D group. This test supports a conclusion that 4D visualization improves the capability of understanding the construction schedule and helps the collaborative decision making in detecting logical errors.

The results illustrated in Figure 6 show that the 4D group made fewer mistakes than the 2D group when they claimed logical errors. The statistical test show that there is less than 5% chance the 2D group can claim the logical errors more accurately than 4D group. It is evident that 4D visualization helped professionals avoid making mistakes in detecting logical errors in every task.

The results illustrated in Figure 7 show that the 4D group detected logical errors faster than the 2D group in every task. The P-value of the statistical test shows that there is at most 6.1% of chance that the 2D group detects logical errors faster than the 4D group. Therefore, it could be determined that 4D visualization helps construction professionals improve their capability to understand the construction schedule and detect logical errors.

The statistical test shows that the 4D group communicated less frequently than the 2D group in the third and fourth task. This demonstrates that 4D visualization could help the participants reduce the frequency of communication to explain logical errors detected. However, sometimes participants communicated more when they used 4D visualization. They discussed not only distinct logical errors but also ambiguous errors such as site congestion, which was one reason that increased the frequency of their communication. However, this kind of discussion was never possible when they only used the 2D drawing and the bar chart.

7. CONCLUSION

The results of the experiment produced empirical evidence that Web-based 4D visualization helps construction professionals understand the construction schedule and supports collaborative decision-making in construction scheduling. Web-based 4D visualization is expected to gain support among the construction professionals for collaboration in construction scheduling.

The experiment was implemented only once with students working in the area of construction. Repeating the experiment would enable verification of results. Use of different population could indicate sensitivity of the instrument. Before repeating the experiment however, the experiment should be modified to track individual's performance in each task so that the impact of individual's characteristics to the results of the experiment can be analyzed.

The impact of 4D visualization on learning is another provocative area of research. One may speculate that 4D visualization would be more effective for teaching principles of project planning and scheduling because it is less abstract than CPM networks or bar charts.

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