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THE SELECTION OF COLOR SCHEME FOR 4D CONSTRUCTION MODEL

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ABSTRACT: This paper presents the *selection, examination, and user test* (SEUT) procedure to determine the ideal color scheme for a 4D model. This systematic procedure can be performed iteratively to obtain the color scheme that would be most appropriate for construction purposes. To verify the proposed procedure, an example case with two iterations is presented. Ten color schemes were examined and 48 users tested during the two iterations, and the result shows that the SEUT procedure is an effective method for determining the ideal color scheme for 4D models.

Keywords: 4D; Constructional Model; Color Scheme; Usability; User Interface

1. Introduction

1.1 Motivation and Background

Four dimensional (3D and time) construction management tools allow engineers to explore a construction project visually. Based on the project's progress, 4D tools integrate 3D models and their corresponding construction schedules into 4D models to assist engineers to allocate resources to a jobsite efficiently. Engineers may explore and examine construction progress by analyzing these 4D models in the virtual world. Consequently, the principal challenge for 4D models is to devise a method which allows users to interpret the models easily and effectively.

A typical 4D model uses a series of colors to represent construction status at a specific time of a project. Animations can also be used to convey temporal information, such as the change of a construction's status over time. From our observation, programmers generally select color schemes based on personal preferences when developing these 4D tools. However, these color schemes may not actually be appropriate for visualizing 4D models. Qualitative colors such as rainbow colors are generally chosen as the basic color scheme to represent different construction states. However, Light and Bartlein [1] have shown that rainbow colors are inappropriate when used to represent sequential data. Therefore, it is necessary to further investigate the selection of color schemes for 4D models.

During the construction process, 4D construction-management tools usually use changes in color to represent changes in the fourth dimension (time) of a construction state. The essential states include: pre-construction, under-construction, and completion. Some complicated 4D models include more state levels, such as a delay state. When viewing a 4D model, users need to remember all the colors and their corresponding states to follow the construction progress correctly; however, memorizing particular colors can become very difficult if a project involves a large number of construction elements and construction states. If the color scheme is not carefully selected, users may end up being confused or even mislead, and as a result, will interpret the construction progress incorrectly.

From a technical point of view, the biggest challenge of presenting 4D models in 2D is how best to present the information. As a result, some computer graphics manipulation techniques must be used. The first technique is to use perspective projections to show the 3D overview; by firstly scaling down the size of objects further away, users will feel that they are actually viewing a 3D scenario. Second, shading is an important technique used to enhance the perceptibility of the image. Shading allows depiction of depth in 3D models on a computer screen by varying the shades of darkness. In this case, 3D models become more distinguishable. Last, colors are applied to show the fourth dimension in a 4D model.

As 4D models combine 3D geometrical models with various construction states represented by colors, they can often impede users from understanding the model correctly, especially if a poor color scheme is chosen. Users then find comprehending the 4D models, which may contain a large number of elements, especially difficult, and because some elements may be obstructed or be similar in color with a neighboring element, users are forced to apply extra effort to interpret the construction information correctly.

In conclusion, choosing the correct color scheme is one of the most important decisions in enhancing the effectiveness of using a 4D model. A color scheme which can clearly display large 3D models with multiple construction states is very important, and since construction projects can vary greatly in terms of size, participants and approach, a systematic procedure which can be used to balance all necessary aspects of a 4D model must be found through further research.

1.2 Research Objectives

In this research, we aim to develop a systematic procedure that can be used to determine the ideal color scheme for 4D models to be used in 4D construction management tools. Since 4D models usually serve different purposes in different construction projects, developers of 4D tools can select the most appropriate color scheme by using this selection process. In this research, we also consider the usability of certain colors in 4D models. When selecting the colors, we need to consider both the perceptional and the psychological capacities of users. Usability tests are also necessary in examining whether the users can easily comprehend the 4D model with equipment setups that are similar to the environments where 4D models may be applied. A realistic example case (for real or potential users) also needs to be designed and tested to validate the procedures developed in this research.

2. SYSTEMATICAL PROCEDURE: SEUT

Figure 1 presents the selection, examination, and user test (SEUT) procedure, a systematic procedure proposed in this research for determining an ideal color scheme for a 4D model. This procedure includes three major steps by which color schemes can be defined and evaluated by users. The whole procedure can also be performed iteratively if the color schemes are determined inappropriate for users' needs. Once the color scheme reaches a certain usability performance in the user test, we can consider it as ideal for a 4D model.

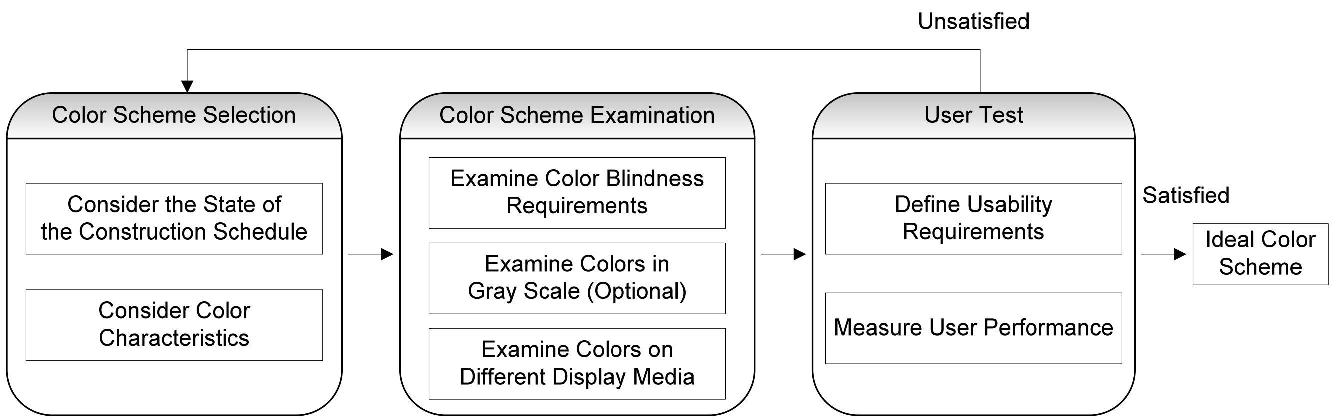


Figure 1. Selection, Examination, and User Test (SEUT) procedure

The first step in the SEUT procedure is to select color schemes taking into consideration the nature of schedule or time information and the color characteristics in construction projects. Multiple color schemes are then identified and passed onto the second step. The second step aims to examine the color schemes through three tests, including color defectiveness, to see whether users who are color blind will have difficulty with the particular color scheme, in gray scale and on different display media. After each test, we ask individual users to determine whether the color schemes fulfill their needs. Usability requirements are also defined and user performances evaluated during each of the processes. Finally, one or more color schemes are identified as a result, which are then passed as input to the next iteration.

Through this procedure, we expect to produce color schemes specifically applicable to 4D models. These color schemes will not only help users recognize the 3D objects but easily, but also increase the degree of understanding toward the construction schedule.

2.1 Step 1: Color Scheme Selection

In this first step, we consider two criteria in selecting the color schemes for 4D models. One is the state of the construction schedule in a 4D model and the other is the characteristics and categories of colors. Using these two criteria, the color schemes that are selected will be able to make best use of the features of the schedule information as well as the colors.

Consider the State of the Construction Schedule

Four-dimensional models represent the schedule information by sequentially displaying the construction status of work items in the 3D geometrical models. In this research, we have chosen a typical 4D model; one that has six construction states, which are (1) pre-construction, (2) under-construction, (3) completion, (4) pre-construction delay, (5) under-construction delay, and (6) completion delay. To represent these statuses on a 4D model, six distinguishable colors are needed.

First, we categorize the construction statuses based on their relationships. The first three statuses, namely, pre-construction, under-construction, and completion, are categorized as the *on-time group*, which are work items that must adhere to a regular schedule. The other three states, pre-construction delay, under-construction delay and completion delay are categorized as the *delayed group* and require extra attention from the decision-makers. Within each of the groups, the three statuses can also be ordered sequentially, and from the schedule information, we set the following three rules for the selection of color schemes for 4D models:

1. Work items in the 4D model can be categorized as belonging to either the *on-time group* or the *delayed group*.
2. Work items in the *on-time group* have ordering relationship A.
3. Work items in the *delayed group* have ordering relationship B.

Consider Color Characteristics

After defining the state of the construction schedule, the next step is to find a matching set of color schemes, and to do so we employ the color categorization method proposed by Harrower and Brewer [2]. Three types of color schemes were investigated in their research: diverging, sequential and qualitative, each of which is used to represent a different meaning. We chose to use diverging color schemes for representing whether the work item has been completed according to schedule, and sequential color schemes for individual ordering relationships. The details of how the diverging and sequential color schemes are selected for representing the schedule information are described as follows:

1. *Diverging color schemes:* We selected cool color schemes to represent the on-time group and these can be considered to be in a normal condition. Cool colors give the feeling of calm and are soothing in nature, thus are suitable for representing the stable and safe construction conditions of the on-time states. Conversely, we selected warm color schemes to represent the delayed group, where the work items in are behind schedule and may cause a chain reaction of delays to affect other work items. As warm colors are vivid in nature and able to arouse or stimulate the viewer, they attract the user's attention and highlight the critical construction conditions of the delayed states.
2. *Sequential color schemes:* Sequential color schemes imply order or sequence. They are usually suitable for representing data that ranges from low-to-high in value either on an ordinal scale, e.g., cold to warm, or on a numerical scale in color space. The ordering relationship of work items in this study can be clearly represented through the use of sequential color schemes. Therefore, we selected three sequential colors schemes to represent the work items in the pre-construction, under-construction and completion states respectively, for both the on-time and delayed groups.

2.2 Step 2: Color Scheme Examination

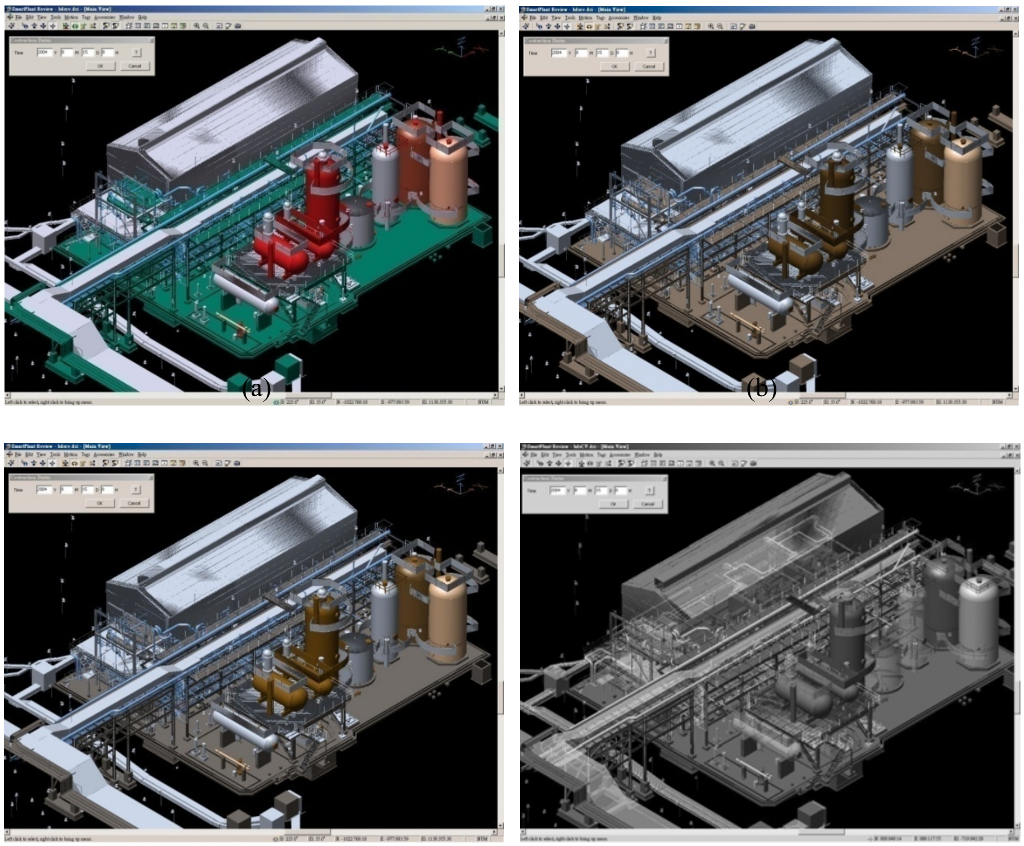
After the first step, we link the construction schedule to the colors by considering their respective states. At this stage, we also take into consideration the perceptual effects of the color schemes, but to do so, we need to first consider whether the color schemes are distinguishable in a real 4D model for all users, including those who have color vision deficiencies. We must also consider the distinguishability between the work items in a gray-scale model as paper-based documents are still the most commonly used medium by which information is presented in construction projects. Furthermore, color deviations between various types of display media also need to be examined to ensure that the same 4D model can be displayed and the information represented clearly in any format. The details of these issues are addressed as follows.

Examine Color Blindness Requirements

We examine the color schemes to eliminate pairs of colors which cannot be distinguished by users who may have certain types of color blindness, which is especially important as there is a large percentage of the population who are affected by some degree of color vision deficiency. Statistically, almost 8% of men and 0.4% of women are colorblind [3], most of whom are only partially color blind and have difficulty distinguishing between red and green. Since the majority of construction engineers are male, choosing color schemes with people who have these vision deficiencies in mind will help avoid color recognition issues for many of the users.

Viewers with a color vision deficiency will see some images differently from viewers with normal color vision. Taking a construction image, viewers with normal color vision will see the image as shown in Figure 2(a). Users affected by protanopia (absence of red retinal receptors) might see image Figure 2(b) and users affected by deuteranopia (absence of green retinal receptors) might see image Figure 2(c). From these three images, we can see that the green and red colors are easily distinguishable by viewers with normal color vision in the example 4D model, however, when transferring the image to protanopic and deuteranopic color visions, colors between red and green become similar to brown and the brightness of warm colors is significantly reduced compared to original, such that only red, orange, and yellow are distinguishable. Users with color vision deficiencies will find it much more difficult to correctly identify the six construction states from the example 4D model because the features of the construction schedule become indistinguishable.

To reduce the problem of perceptual difference between users shown in Figure 2(a), (b) and (c), we propose that all the color schemes developed using the first step must go through an examination of color blindness requirements by using the simulation algorithm published by Brettel et al. [4] and implemented by Dougherty and Wade [5]. After generating these computer-simulated images, we will then only choose to accept color schemes if they are distinguishable by both users with and without color vision deficiencies.



(c) (d)

Figure 2. The 4D model simulated under different restrictions: (a) normal color vision; (b) protanopic color vision; (c) deuteranopic color vision; (d) gray scale

Examine Colors in Gray Scale

After taking color blindness requirements into consideration, we further examine the color schemes using gray scale print-outs, which are commonly used in project presentations, during meetings, and, more importantly, are cheaper than using color printouts. Therefore, it is relevant to consider how the information is transformed between the color 4D models to gray scale print-outs.

In most computer systems, the image conversion between color pictures and gray scale printing follows the perception of luminance in the human visual system. International Telecommunications Union – Radiocommunications [6] has defined the relationship between luminance and RGB values in ITU-R BT.601. They suggest a log-average luminance value calculated by finding the geometric mean of the luminance values for all pixels, whereby in gray scale printing, the luminance value is used as the pixel value.

In this research, we used the following equation to transfer color images to gray scale images for every pixel.

$$Y = 0.299R + 0.587G + 0.114B \quad (1)$$

where Y is the luminance value of the pixel in the gray scale image and has a range of 0–1; R is the value of red color component; G is the value of green color component; B is the value of blue color component.

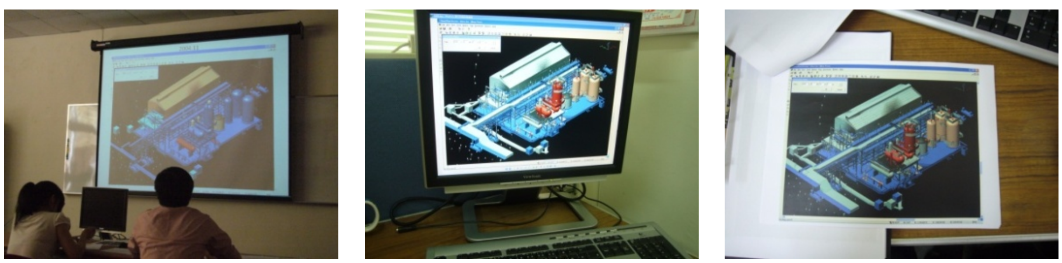
Figure 2(d) shows the gray scale version of the example image in Figure 2(a). For colors in gray scale, we also attempted to verify the distinguishability of color schemes in gray scale print-outs. However, after many trials, we discovered that it was extremely difficult to find the ideal distinguishable color scheme for a 4D model with six construction states. The main reason being that the display range of gray scale is limited compared to the display range of the color scale; furthermore, we also found it very difficult to represent the diverging and sequential relationship of the schedule information using only gray scale. Therefore, we suggest that the gray scale examination be used only for optional examination. Alternatively, it can be applied to 4D models with fewer construction states (we recommend less than or equal to four), otherwise information may be lost or become misleading.

Examine Colors on Different Display Media

In addition to the composition of colors for the color blindness and gray-scale display tests, different types of display media is another essential factor to the perceptual effects of color schemes on 4D models. Color appearance greatly rely on display media, thus examining the distinguishability of color schemes on different display media is necessary for finding an appropriate color scheme for 4D models. In this research, we further examine the color schemes by displaying an example 4D model on the three most commonly available display media in construction offices, which are: LCD projector, LCD monitor, and laser printer color print-outs.

Since the three display media are very different in terms of their image rendering and their working environments, the colors shown by each display media are rarely consistent. For example, LCD projectors produce colors by projecting light onto a projection screen, and usually work best in a low illumination environment that avoid influence from ambient lights in the surrounding environment. LCD monitors, on the other hand, produces colors by projection through color filters between crystal molecules in a flat thin panel. They are able to produce clear and consistent images, but are limited in screen size, which is especially troublesome for multiple viewers. As for paper-based printing, the color is produced by attaching the color ink pigments to the paper, and is very commonly used for meetings and discussions due to its low cost, high resolution, excellent portability and flexibility in diverse environments.

Figure 3 shows the procedure used to examine the color scheme's distinguishability on different display media. During the process, we verify an example 4D model with the same color scheme on a LCD project, a LCD monitor, and a paper print-out. The purpose of this verification is to check the distinguishability and see if there are obvious color deviations between these display media using the same color scheme. Once the example 4D model is deemed acceptable, especially for recognition of a construction schedule, we then classify the color scheme as a user-friendly color scheme for 4D models using different display media.



(a) (b) (c)

Figure 3. Examining the distinguishability of color schemes using different display media: (a) LCD projector, (b) LCD monitor, and (c) laser printer color print-outs

2.3 Step 3: User Test

We have selected and examined the color schemes in the previous two steps, and in Step 3, we start focusing on the users. We would like to verify whether color schemes can be used effectively to help users recognize and understand the 4D models. We also would like to investigate whether users can effectively identify the problematic work items and probe various flaws in the schedule by understanding information from the color schemes. Furthermore, the psychological effects of various color schemes on the users are also considered. To achieve this, we first need to define the usability requirements as well as the quantitative and qualitative methods used to measure user performance. This will allow us to verify whether the color schemes actually fulfill the users' needs. The following sections explain the requirements in more detail.

Define Usability Requirements

In general, usability requirements represent the users' expectations and desired user reaction to a color scheme. The requirement usually begins from a series of work scenarios and is refined through further research and meetings with potential users. Therefore, we have to define the potential users first in order to capture the users' needs and define the usability requirements. In this paper, we regard potential users as people who have opportunities to explore 4D models at present and in the near future.

Because each set of potential users may have different expectations, needs and difficulties in using color schemes (e.g., task performance, satisfaction, and learnability), we employed two methods to define usability requirements. The first method is to allow the users to define their own requirements. We do this through interviewing, observing and conducting surveys to collect opinions from potential users that have been identified. The second method is to use the usability framework published by Quesenbery [7], a well-known framework frequently used in usability tests.

This framework defines usability requirements using five dimensions (5Es): (1) Effective, (2) Efficient, (3) Engaging, (4) Error Tolerant, and (5) Easy to Learn. The individual weighting of the dimensions can vary depending on the features of the user tests to reflect the importance of each dimension. In the SEUT procedure, we integrate these two methods to define usability requirements.

Measure User Performance

After defining potential users and usability requirements, we move on to designing the corresponding usability test to measure user performance. In doing so, we propose a double-blind design in an attempt to eliminate subjective bias of colors on the part of both subjects and experimenters. First, we assemble a team consisting of a facilitator, an observer, and participants recruited from a pool of potential users. The facilitator will be in charge of running the simulated project meeting while the observer records the entire process, including the interaction between the participants and the color schemes on the 4D models. The participant will also be asked to carry out realistic tasks to inspect the design of color schemes. Here, we place special focus on the user's experiences with the color schemes under the actual conditions of use.

Based on the work scenarios of the 4D models we have previously collected, the tasks are simulated under real situations. These tasks are used to collect both quantitative and qualitative data that reflect the user's performance. The participants are asked to examine a 4D model that uses color schemes we developed in the previous two steps and then to respond to specific questions. The usability methods include the thinking aloud method, observation, and questionnaire. We also propose using high-fidelity prototyping by mimicking a real simulation of a 4D project in a controlled environment. The user performance can be treated as a baseline or control measurement, so if a color scheme passes a predefined user performance acceptability level through the user test, we consider the color scheme as an ideal color scheme for 4D models.

3. EXAMPLE CASE

To verify the proposed procedure, an example case with two iterations was performed in this research. We selected a real project as the example case: a plant construction project, including approximately 20,000 elements in the 3D model with a project duration of approximately two years. In this example case, we wanted to re-examine the original color scheme used in Construction Director, an in-house 4D software developed by Hsieh et al. [8], and attempted to improve the usability of the color schemes by following the SEUT procedure.

In Construction Director, six construction states are shown in the 4D model by using six distinguished colors. The six states are: (1) pre-construction, (2) under-construction, (3) completion, (4) pre-construction delay, (5) under-construction delay, and (6) completion delay. When developing Construction Director, the developers selected the colors based only on their distinguishability from each other. The original color scheme for the six states in Construction Director is presented by the color scheme SU shown in Figure 4(a).

After the first iteration, we identified multiple color schemes that were suitable for use in displaying 4D models. Since it was the first iteration, we chose to investigate the interaction between users and color schemes of only a small number of users. Moreover, we wanted to confirm whether color schemes affect the use of 4D models, and in particular whether it can predict the essential factors which influence the participants' perception of 4D models. We began by selecting seven color schemes for the first iteration, six of which were determined by using diverging-sequential relationship using the SEUT procedure, while the last one was chosen to disobey these rules in selecting color schemes. This experiment was designed to test our hypothesis to see whether the diverging-sequential color schemes can really be helpful for users in understanding the 4D model. We then checked the distinguishability of these color schemes for color blindness and different display media based on the SEUT procedure.

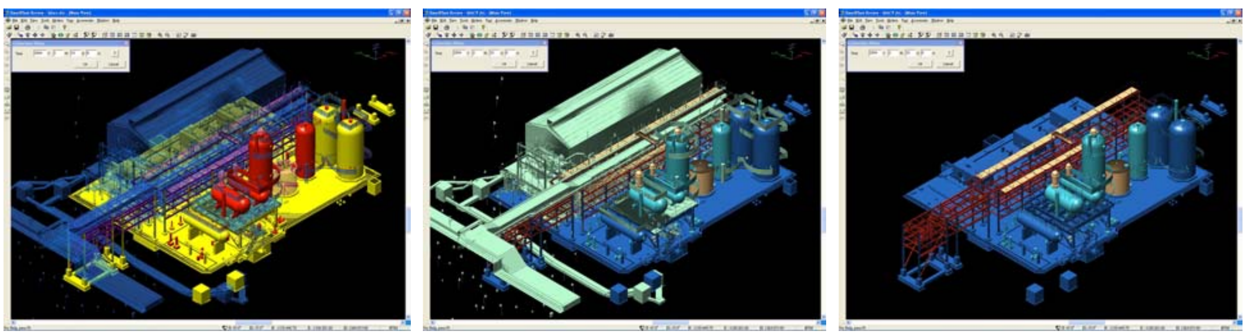
After the selection and examination of color schemes, we performed a user test. In the user test, we aimed to confirm our hypothesis that using diverging-sequential color schemes in 4D models can increase a user's understandability of the models. We began by measuring a user's performance by simulating a 4D project meeting with ten engineers from different backgrounds. The participants were asked to identify the construction states of the 4D model and then answered several questions regarding the different color schemes. The results agreed with our initial prediction that following the rules of selecting diverging-sequential color schemes allows for better user performance compared to schemes where the algorithm does not adhere to the rule.

After obtaining the results from the first iteration, we were able to confirm that the diverging-sequential color schemes can improve a user's comprehensibility of 4D models. We also eliminated the use of transparent colors as we found that they may actually confuse the users. During the second iteration, we investigated whether six colors are needed to represent six construction states, or can five or less give a similarly acceptable result. We also included more participants during this iteration to investigate the statistical effects of the test results. We began with the results from the first iteration and followed the SEUT procedure to select, evaluate and test the colors. After this procedure, we hypothesized that we would be able to determine a set of color schemes that can be used in Construction Director.

During the selection of color schemes in the second iteration, a well-considered color scheme SA, which is shown in Figure 4(b), was developed by using the SEUT procedure, starting with the color schemes from the first iteration. We also checked its distinguishability using procedures similar to that of the first iteration. The color scheme was then analyzed from the point of view of protanopic and deuteranopic users. We also tested the color scheme by using a LCD projector, a LCD monitor, and by paper print-out to see whether the distinguishability was sufficient for recognizing the construction states in a 4D model.

Through the user test in the second iteration, we wanted to verify whether the color schemes developed by the SEUT procedure are significantly better than the original color scheme used in Construction Director. Besides, we included color scheme SB, shown in Figure 4(c), which particularly hides the pre-construction status from color scheme SA to see the influence of hidden states. An extensive user test with 48 participants was then conducted. These participants included civil engineers, graduate students, and college students of various backgrounds. The participants were also all potential users of 4D models either presently or in the near future. By interviewing these potential users, we further uncovered that the usability requirements of color schemes in 4D models is best analyzed using four of the 5Es (Quesenbery), which are *Effectiveness*, *Efficiency*, *Ease of Engaging*, and *Ease of Learning*. Based on these usability requirements, we then measured user performance by asking participants to complete simulated 4D tasks with different color schemes.

Figure 5 shows the descriptive statistical results, including mean value and standard deviation for four assessments. The results revealed that the color scheme developed by the SEUT procedure is significantly better than the original color scheme in Construction Director in the aforementioned four assessments from the usability requirements. Especially in the areas of *Ease of Engaging* and *Ease of Learning*, using an α level of 0.05, the resulting scores were much higher than the color scheme originally used in Construction Director ($p < 0.001$).



(a) (b) (c)

Figure 4. Color schemes comparison in the second iteration of the example case: (a) SU, original color scheme used in Construction Director; (b) SA, color scheme developed through two iterations of the SEUT procedure; (c) SB, color scheme particularly hides the pre-construction status from color scheme SA

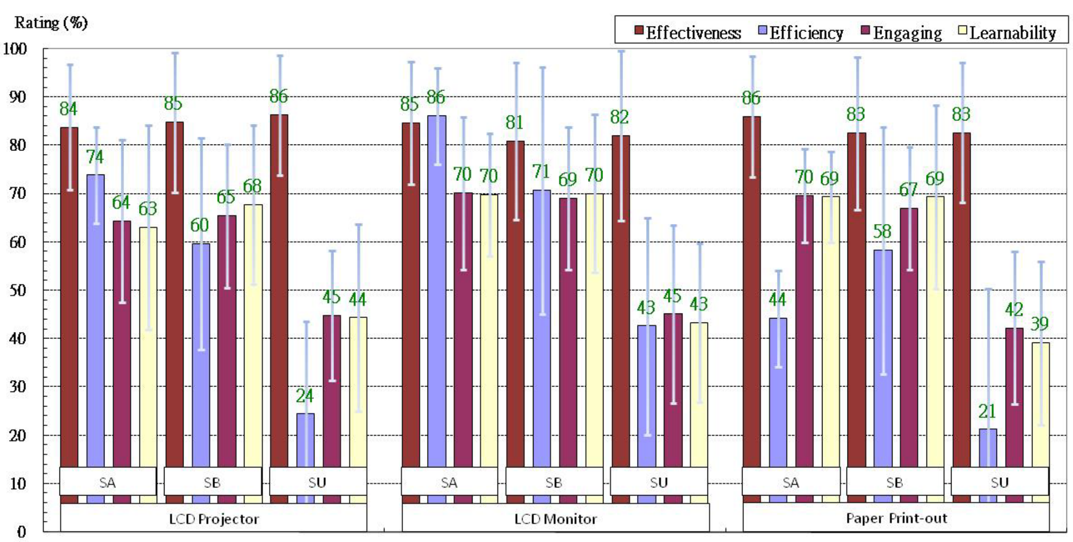


Figure 5. Test results in the second iteration of the example case

4. CONCLUSIONS

From the two iterations of the SEUT procedure in the example case, we were able to make the following five conclusions:

1. *A diverging-sequential color scheme is ideal for representing the states of 4D models*: By following the rules of selecting diverging and sequential color schemes, we found that users were able to understand the 4D model more easily.
2. *Do not use half-transparent colors*: From the observations made and the interviews, we found that half-transparent colors blended in with the background color too easily, which causes confusion amongst users and obtained a lower score in the user tests. This phenomenon becomes evident when viewing larger 4D models.
3. *"Hidden states" should be used with caution*: During the second iteration of the user test, we compared two color schemes that had the same color scheme but one had the pre-construction state hidden. We found that hiding one state actually hinders the user's judgment, and the user is forced to make a mental leap from one color to another. This may actually lower their understanding of the entire model. However, when paper print-outs were analyzed, fewer colors were found to actually reduce a user's efforts in short-term memory, resulting in a higher recognition scores.
4. *Better usage of color schemes may reduce a user's mental efforts when using 4D model*: Comparing the color scheme we selected using SEUT procedure with the original color scheme from Construction Director, we found that the former performed much better in both the Ease of Engaging and Ease of Learning requirements. From our observations, the participants become aware of the design logic (i.e., through diverging and sequential colors) behind the color scheme a lot faster, which also reduced the amount of effort required on their short-term memory. This will enhance the overall experience of using the 4D model.
5. *Influence of display media is significant*: From the user tests in both iterations, we found that the display media is always an influential factor on the usability performances of the color scheme. We also found that examining the color schemes in the display media before user tests is very important and non-ideal color schemes can actually be eliminated during this step; in turn, this reduces wasted time spent on asking users to examine inappropriate color schemes.

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