STUDY FOR ESTABLISHING DESIGN GUIDELINES FOR MANUALS USING AUGMENTED REALITY TECHNOLOGY

Verification and Expansion of the Basic Model Describing "Effective Complexity"

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Abstract: Augmented reality (AR), a technology that enables users to see an overlay of digital information on the real view, is expected to be applied more and more to human factor innovation. It has been suggested that a manual using AR (AR manual) improves accuracy and efficiency in actual work situations. To make an AR manual practical, hardware such as see-through display or retinal scanning display has been actively developed. However, software, i.e., information provided by the AR manual, has not been sufficiently examined. In a recent study, the authors built a mathematical model that describes the "effective complexity" of an AR manual according to the complexity of the real view. In this study, the basic model is verified by applying it to the AR manual for a realistic task. Furthermore, the applicability of the basic model is examined by assuming two different situations where either accuracy or efficiency has high priority. The objective of this study is to establish rough but practical guidelines for designing an AR manual.

1 INTRODUCTION

In recent years, the applicability of augmented reality (AR), a technology that enables superimposition of the real view and digital information (Wellne et al., 1993) to manuals used in actual work situations, has been discussed. For example, when a manual is available to a worker through a see-through head-mounted display (HMD), he/she can see it superimposed on his/her real view. Such AR manuals are considered to reduce human errors and enhance task efficiency, because they allow workers to easily compare a real object with related information (Azuma, 1997)(Feiner, 2002). Moreover, as HMD technology is improving rapidly, the hardware for AR manuals has become almost ready for practical use. However, the software has not yet reached this stage, because requirements for designing information provided by HMDs are not sufficiently clear. Thus, it is necessary to establish guidelines for designing AR manuals, which will differ from those for paper-based manuals.

In a previous study (Nakanishi et al., 2008), the authors examined how workers' performance changed depending on the layout of information given by an AR manual through an experiment in which real-world conditions were generated by a computer program and presented on a monitor. From the results, the authors built a model that provided the most effective design of AR manuals according to the real-world conditions (described more specifically in the next section). We have positioned that model as the basic model, which will be fundamental to the guidelines for designing AR manuals.

As the next step, we verify and expand the basic model through another experiment in which a task was performed not under computer-generated conditions, but under real conditions. The objective of this study is to analyze the relationship between the design of AR manuals and task performance in

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conditions similar to actual work situations, and suggest how to expand the basic model to practical guidelines for designing AR manuals.

2 KEY IDEA OF THE BASIC MODEL

In general, the real-world conditions in front of a worker's eyes cannot be controlled. Thus, we attempt to clarify how AR manuals should be designed when a condition of the real view is given.

For example, when excess information is overlaid on an object in the real view, visibility may decrease. On the other hand, when information is overlaid on an object unit by unit, the worker is required to switch the overlay repeatedly in a task sequence.

In our previous study (Nakanishi and Okada, 2006), we performed an experiment in which different real-world conditions were virtually generated. We found that when the real view was relatively uncomplicated, task performance was affected more by switching images of the AR manual than by seeing excess information. Conversely, when the real view was complicated, task performance was affected more by seeing excess information than by switching images of the AR manual. When these two factors were balanced, task performance was the highest. Based on these results, we built a model that describes the most effective design of AR manuals according to real-world conditions, as follows.

First, we considered two aspects of task performance, "accuracy" (lack of errors) and "efficiency" (speed). Assuming that both accuracy and efficiency were equally necessary and important, we defined "damage to task performance" (DP) using both error rates (E) and unit operation time (T).

$$DP = 0.5S(E) + 0.5S(T) \quad (1)$$

S(E): Standardized E
S(T): Standardized T

Second, we quantified the conditions of visual information based on the idea of "complexity." In general, the more crowded the items are, the more complex the information looks. Thus, we defined complexity (C) as the number of items to be attended to (n) divided by their dispersion (M). M was defined as the standard deviation of the distance from each item to the center of them (d_i: i = 1, 2,..., n) divided by the mean of the distances ($\bar{d}$), so that C did not depend on measurement of d_i.

$$C = n / M = n\bar{d} / \sqrt{\sum_{i=1}^{n} (d_i - \bar{d})^2 / (n-1)} \quad (2)$$

We examined the data obtained from the experiment and found that the relationship between the complexity of the real view (C_R), complexity of the AR manual (C_A), and DP could be expressed by the following equation.

$$\overline{DP} = (2.57\times10^{-4} C_R + 8.71\times10^{-1})(6.63\times10^{-3} C_A - 8.76\times10^{-1}) + (1-(2.57\times10^{-4} C_R + 8.71\times10^{-1}))(\frac{1.00\times10^{+2}}{C_A + 6.22}) - 3.00) \quad (3)$$

Moreover, we suggested that when C_R was given, C_A that minimized $\overline{DP}$ could be determined by the following equation.

min. $\overline{DP}$

$$\hat{C}_A = \sqrt{\frac{1.00\times10^{+2}(1-(2.57\times10^{-4} C_R + 8.71\times10^{-1}))}{6.63\times10^{-3}(2.57\times10^{-4} C_R + 8.71\times10^{-1})}} - 6.22 \quad (4)$$

Equation (4) provides the "effective complexity" of AR manuals according to the complexity of the real view. Accordingly, it can be regarded as the basic model, which describes effective design of AR manuals using the number and dispersion of information items.

3 METHOD

In this study, we applied an AR manual that was designed according to the basic model, not to a computer-generated task but to a realistic task, and examined the practicability of the model by evaluating task performance.

3.1 Experimental Task

A wiring task, in which a subject plugged many lines into a panel, was chosen as the experimental task, because it has been proven that task performance improved when subjects used an AR manual compared to when they used a paper-based manual in the same task.

The fixed panel (280 mm × 300 mm) included randomly arranged holes (r = 3.5 mm) to be plugged. Figure 1 shows an example pattern of the panel. An HMD displayed the AR manual corresponding to each pattern. Figure 2 shows an image of the AR manual. The AR manual indicated which colored lines should be plugged into which holes on the

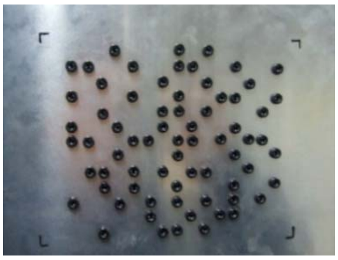

Figure 1: Example of panel pattern.

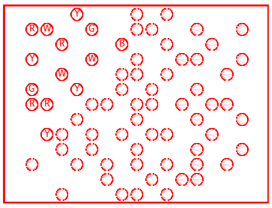

Figure 2: Image of AR manual.

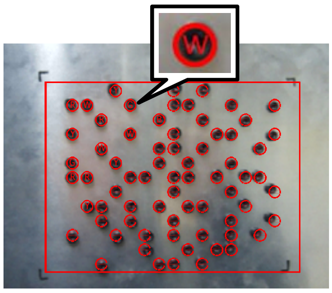

Figure 3: Superimposition.

Figure 4: HMD.

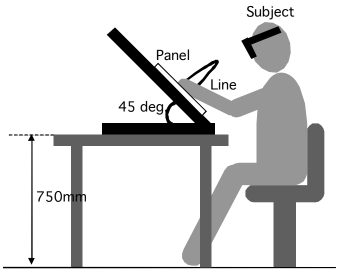

Figure 5: Experimental environment.

panel. (Y: yellow, G: green, R: red, W: white, B: blue).

A subject wearing the HMD faced the panel and performed the task. The frames were drawn on both the panel and the AR manual, so that he/she could see them superimposed by adjusting his/her own position and angle according to it (see Figures 3–5).

The subject's task was to plug lines into all the holes on the panel according to the AR manual. The subjects were required to complete the task correctly and quickly. Even if they recognized their own errors, they were not allowed to correct them. A subject started the task when the AR manual was displayed on the HMD, and finished when all of the holes on the panel were plugged.

3.2 Experimental Conditions

To set different conditions for the real view, five panel patterns were prepared (Figures 6-1–6-5). The AR manual was displayed in the following three ways: "one-by-one indication" (each hole was indicated one by one), "all-once indication" (all holes were indicated at once), and "model-based indication" (which holes were indicated at once was determined according to the basic model). Specifically, model-based indication was given as follows. First, substituting each value of complexity for each panel pattern (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}) in equation (4), the value of the effective complexity of the AR manual (C_{An}: n = 24,

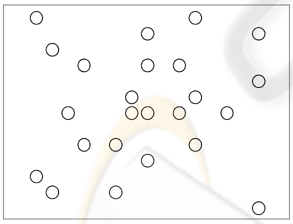

Figure 6-1: Pattern of panel (CR = 44.8, n = 24).

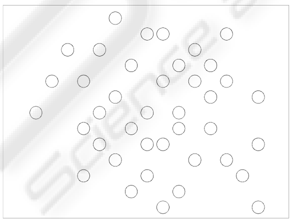

Figure 6-2: Pattern of panel (CR = 96.3, n = 40).

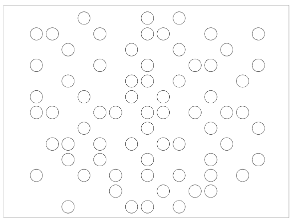

Figure 6-3: Pattern of panel (CR = 174.6, n = 70).

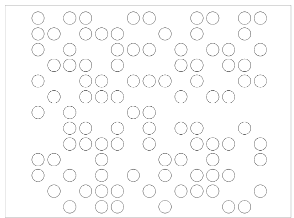

Figure 6-4: Pattern of panel (CR = 271.4, n=100)

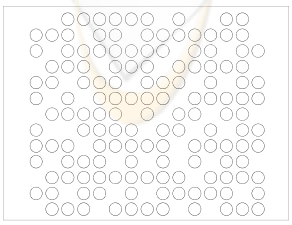

Figure 6-5: Pattern of panel (CR = 391.2, n=144).

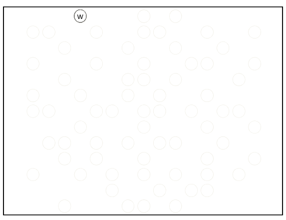

Figure 7-1: One-by-one indication (CR = 174.6).

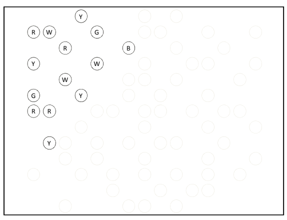

Figure 7-2: Model-based indication (CR = 174.6).

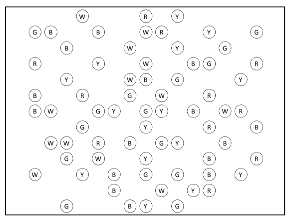

Figure 7-3: All-once indication (CR = 174.6).

Table 1: Complexity of panels, effective complexity of AR manuals, and frequency of switching indication.

Number of holes (n)	Complexity of Panels (C_R)	Efective Complexity (C_A)	Frequency of Switching Indication (one-by-one)	(model-based)	(all-once)
24	44.8	33.3	23	2	0
40	93.6	31.3	39	3	0
70	174.6	27.9	69	5	0
100	271.4	22.8	99	8	0
144	391.2	14.2	143	14	0

follows. First, substituting each value of complexity for each panel pattern (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}) in equation (4), the value of the effective complexity of the AR manual (C_{An}: n = 24, 40, 70, 100, 144) was given for each panel pattern. Second, the dispersion of the holes on each panel pattern (M_n: n = 24, 40, 70, 100, 144) was given as described in section 2. Third, substituting each M_n in equation (2), the number of holes to be approximately indicated at once was determined for each panel pattern. Table 1 shows the values of C_A the "effective complexity" of the AR manual, corresponding to each panel pattern. Moreover, Figures 7-1–7-3 show example images of the one-by-one, all-once, and model-based indication corresponding to one of the panel patterns.

In this experiment, 15 conditions (5 real-world conditions * 3 conditions of the AR manual) were tested.

In the case of one-by-one or model-based indication, the subject had to switch the image from one hole to the next or from one part of the panel to the next with a handy button. Table 1 shows how many times the indication image was required to be switched in each condition.

3.3 Experimental Settings

Eighteen students (age 21 to 25 years) with good vision participated in the experiment. After they repeated the procedure of the task in each condition for training, they performed the task once in each condition for data recording. Then the order of the three indication patterns of the AR manual was alternated within each condition of the real view. The HMD was a retinal scanning device (NOMAD, made by Microvision, Inc.). The transparency to the real view was almost 100%. The image of the AR manual was drawn in monochrome red.

During the task, subjects' actions were recorded with a digital video camera, and the time taken for the task was automatically recorded. Moreover, after the task, the panel with lines was compared with the AR manual, and errors were noted.

4 RESULTS

To examine the task performance for each condition, in particular, the condition in which model-based indications were provided by the AR manual, we analyzed the data in terms of accuracy and efficiency.

4.1 Error Rate

The following errors were observed: omitting plugging, plugging wrong-colored lines, and plugging to wrong holes. The solid lines in Figures 8-1–8-5 show the error rates for each condition of the real view (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}). In each chart, the left vertical axis is scaled individually, in order to focus on how the error rates changed according to the indication pattern of the AR manual under the given condition of the real view.

The error rate was high in the case of all-once indication for any condition of the real view. However, it tended to be low in the case of one-by-one indication for most real-world conditions. In addition, it was not always that the error rate became low in the case of model-based indication.

4.2 Unit Operation Time

Plugging a line into a hole was defined as the unit operation. The dotted lines in Figures 8-1–8-5 show the unit operation time in each condition of the real view (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}). In each chart, the right vertical axis is scaled individually, for the same reason as above.

The unit operation time tended to be short in the case of model-based indication, however, it was longer in the case of one-by-one indication that required subjects to switch the image of the AR manual, than in the other cases, in particular, when the complexity of the real view was comparatively low.

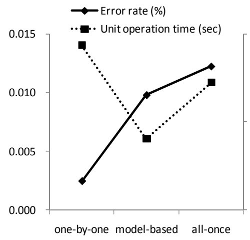

Figure 8-1: Error rate per task and unit operation time (CR=44.8, n=24).

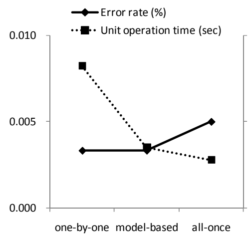

Figure 8-2: Error rate per task and unit operation time (CR=96.3, n=40).

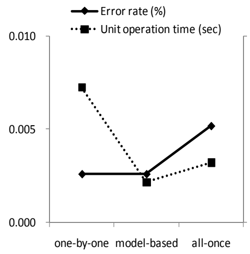

Figure 8-3: Error rate per task and unit operation time (CR=174.6, n=70).

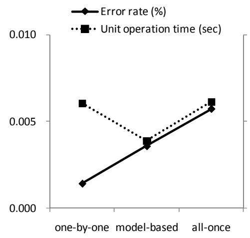

Figure 8-4: Error rate per task and unit operation time (CR=271.4, n=100).

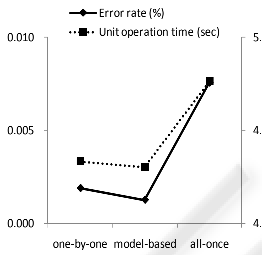

Figure 8-5: Error rate per task and unit operation time (CR=391.2, n=144).

* In Figures 8-1 to 8-5, the left-hand axis corresponds to error rate (%), expressed by the solid line, and the right-hand axis corresponds to unit operation time (s), expressed by the dotted line.

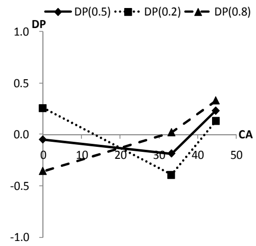

Figure 9-1: Damage to task performance (CR=44.8, n=24).

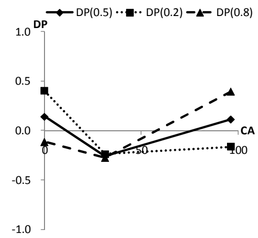

Figure 9-2: Damage to task performance (CR=96.3, n=40).

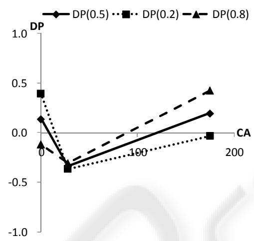

Figure 9-3: Damage to task performance (CR=174.6, n=70).

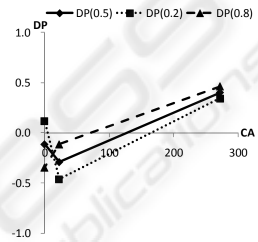

Figure 9-4: Damage to task performance (CR=271.4, n=100).

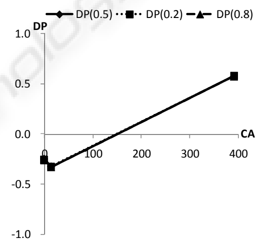

Figure 9-5: Damage to task performance (CR=391.2, n=144).

** In Figure 9-1 to 9-5, the solid line shows DP(w = 0.5), the dotted line shows DP(w = 0.2), and the dashed line shows DP(w = 0.8). The horizontal axis indicates the complexity of the AR manual. Accordingly, in any chart, the middle plot indicates the value of DP in the case of model-based indication.

5 VERIFICATION & EXPANSION OF THE BASIC MODEL

As described in section 2, the basic model was built under the assumption that accuracy and efficiency are equally significant for evaluating task performance. However, in actual situations, there are cases in which workers absolutely should not make errors even if it takes time to do so, and cases in which they have to complete a task within a limited time, wherein a few errors are permitted.

In this section, first the applicability of the basic model is checked under the assumption that accuracy and efficiency are equally weighted. Second, the applicability of the basic model is discussed under the assumption that either accuracy or efficiency is more heavily weighted.

5.1 Verification of the Basic Model

According to the basic model, DP can be calculated for each condition by substituting E and T data in equation (1) (see section 2). The solid lines in Figures 9-1–9-5 show the values of DP in this case.

DP is minimized in the case of model-based indication for any condition of the real view, indicating that the AR manual designed according to the basic model enhances task performance. This suggests that the basic model describes effective design of an AR manual not under computer-generated conditions, but also under the real conditions, if it is assumed that accuracy and efficiency are equally important for the situation.

5.2 Expanding the Applicability of the Basic Model

Assuming cases where either accuracy or efficiency is more heavily weighted, damage to performance (DP (w)) is redefined as follows.

$$DP(w) = wS(E) + (1 - w)S(T) \quad (5)$$

In the discussion below, two different cases are simulated.

Case 1) Efficiency is weighted more heavily than accuracy (w = 0.2).

$$DP(w) = 0.2S(E) + 0.8S(T) \quad (6)$$

Substituting the data of E and T in equation (6), DP(0.2) in each condition of the real view (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}) is calculated, as shown by the dotted lines in Figures 9-1–9-5.

Like DP(0.5), which is expressed by the solid line, DP(0.2) is lowest in the case of model-based indication for any condition of the real view. This indicates that the basic model is also applicable to cases where efficiency has higher priority than accuracy.

Case 2) Accuracy is weighted more heavily than efficiency (w = 0.8).

$$DP(w) = 0.8S(E) + 0.2S(T) \quad (7)$$

Substituting the data of E and T in equation (7), DP(0.8) for each condition of the real view (C_R = {44.8, 96.3, 174.6, 271.4, 391.2}) is calculated, as shown by the dashed lines in Figures 9-1–9-5.

In some real-world conditions (C_R = 44.8 and 271.4), DP(0.8) is minimized in cases other than model-based indication. However, DP(0.8) tends to be low in the case of one-by-one indication for any condition of the real view. This suggests that one-by-one indication should be used in situations where accuracy has higher priority than efficiency.

In summary, the effectiveness of the basic model depends on whether accuracy or efficiency is more important in a particular situation. In fact, it is difficult to quantitatively estimate the weight of each in real situations. However, we roughly recommend that AR manuals designed according to the basic model should be used in most situations, but AR manuals should provide information unit by unit in situations where errors have to be strictly avoided.

6 CONCLUSIONS

In this study, we applied the basic model not to computer-generated conditions, but to realistic conditions and verified its effectiveness. Further, we examined the applicability of the basic model to different situations.

Essentially, both accuracy and efficiency are important in actual situations, and it is not appropriate to determine the weight of each. However, AR manuals are expected to be widely used. Thus, even rough guidelines considering different situations in designing such a manual will be helpful. In future studies, we will validate the model, and demonstrate feasibility for actual field use.

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