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Assessment of various display devices on a virtual reality-based hand rehabilitation system

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SUMMARY
The purpose of the present study is to assess the effect of an auxiliary lateral image and display devices on manipulation performance in a virtual reality-based hand rehabilitation system. The system consists of a personal computer, a tracker, a data glove, and a display device. For this study, a projector, a monitor, and a head-mounted display were respectively used as the display devices to present three-dimensional virtual environments. Twelve volunteers were recruited to take a pick-and-place procedure at different levels of difficulty. Task time and collision frequency were the parameters used to evaluate the manipulation performance. It was found that the presence of an auxiliary lateral image was a significant factor only for the performance of the projector group and the monitor group. In addition, no statistically significant difference was found in the comparison between the projector group and the monitor group.

KEYWORDS: Virtual reality; Hand rehabilitation; Display device.

1. INTRODUCTION

The importance to patients and society of hand rehabilitation systems has already been recognized in previous studies,[1] and the existing literature on the development of hand rehabilitation systems using virtual reality technology has been reviewed.[1] Under adequate therapeutic supervision, patients could successfully use a personal virtual reality-based hand rehabilitation system at home. They would benefit from regular rehabilitation exercises using this kind of system.

Virtual reality (VR) is a computer graphic technology that can be used to create fictitious objects and events which simulate realistic, three-dimensional scenes and allow elements of a scenario to be manipulated.[2,3] In the virtual environment created by VR technology, visual display is the most important component because it can convey more information to people than any other feature. In most cases, how realistic people feel that the VR environment is depends on the visual display device. The visual display devices broadly used in current VR-based hand rehabilitation systems are projectors, desktop computer monitors, and head-mounted displays.

Most people like to manipulate VR simulators with a projector, since projected images on a big screen can prevent eyestrain and make users more comfortable. By adding more projectors and screens, users are surrounded by graphics and feel more immersed in the virtual environment. But with these additions, further issues such as calibration and synchronization arise,[4] which should be investigated further. In addition, projector costs are high.

On the other hand, the desktop computer monitor is a fairly widespread display device. The cost of this basic equipment is low. However, the scale of objects in the virtual environment created by computer monitors is often not one to one.[5] Consequently, the user feels a low level of immersion or even non-lmmerslon.

Head-mounted display (HMD) is the third choice. It is a very new technological product. HMD displays images with two tiny screens[6] in front of eyes. It can provide a very high level of immersion. But the cost is high. In addition, it has drawbacks such as a shortage of the peripheral vision, and over weight.[7] Users would therefore feel discomfort using HMD over a period of time.[8]

Each display device has advantages and disadvantages in its role in the VR-based hand rehabilitation system. However, the effect of various display devices on the performance of VR-based hand rehabilitation system has not yet been systematically investigated. System developers still face the question of whether or not a projector or HMD is really helpful for users in performance, and whether users feel that they provide a realistic environment that is easy to manipulate, thus making it worthwhile to develop.

To understand the value of different display devices used in the VR-based hand rehabilitation system, the present study assessed their effects on manipulation performance. Twelve volunteers were recruited to undertake a pick-and-place procedure at different levels of difficulty. Task time and collision frequency were the parameters used to evaluate the manipulation performance. Three-dimensional virtual environments were developed using Virtual Reality Modeling Language (*VRML*). This system consists of a personal computer, a tracker, a data glove, and a display device. A projector, a monitor, and a head-mounted display were respectively used as the display device in this

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Table I. Detailed test conditions for each subject.

	Projector group				Monitor group				HMD group			
	1	2	3	4	5	6	7	8	9	10	11	12
1–10 trials	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
11–20 trials	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y

Note. Y = with an auxiliary lateral image.
N = without an auxiliary lateral image.

study. The results of average task time and collision frequency were analyzed using statistical methods to assess the effectiveness of different display devices.

2. METHOD AND MATERIAL

2.1. Subjects

The subjects recruited in this study were twelve healthy and non-disabled right-handed male volunteers. They were randomly assigned to three groups, four subjects in each group, using respectively a projector, a monitor, and a head-mounted display as the display device for tests. All subjects were informed of the test requirements and asked to give their formal consent to participate in the experiment.

2.2. System configuration and test procedures

The VR-based hand rehabilitation system consisted of a personal computer, a tracker, a data glove, a display device and three-dimensional virtual environments. It was the same system as the one used in our team's previous study. The test was also a pick-and-place procedure, carried out as before. The detailed system configuration and test procedure have already been described in the previous study.[1]

2.3. Experimental design and measures

The study was designed to execute a pick-and-place procedure at different levels of difficulty in a pre-test and a main test. The three levels of difficulty designed for and used in the previous study[1] were also employed here. Twelve subjects were assigned equally to three groups, named respectively the projector group, the monitor group, and the HMD group.

The pre-test was taken to assess whether there was any difference between the three groups. The groups all executed the pre-test ten times using a monitor, without any auxiliary lateral image, as the display device. The test results of the task time (the period of time in seconds from grasping the object to releasing it) and the collision frequency (the number of collisions between object and hole) at each level of difficulty were analyzed using an analysis of variance (ANOVA). Any result achieving a probability level that was smaller than 0.05 ($p<0.05$) was considered as statistically significant.

The effects of an auxiliary lateral image and various display devices on the system performance were studied in the main test. The test was taken after the pre-test confirmed that there was no difference among the three groups. Subjects carried out the pick-and-place procedure with or without an auxiliary lateral image in each trial. The groups used their respective display devices. The procedure was undertaken twenty times in total. Detailed test conditions are listed in Table I. In each group, some subjects completed the first ten times with the help of an auxiliary lateral image, then without it in the second ten times. The other subjects took the reverse sequence in the test. Task time and collision frequency at various levels of difficulty were recorded and analyzed with a two-factor (display device and auxiliary lateral image) analysis of variance.

Then the data were further analyzed for multiple comparisons of display devices using the Tukey test that is a post-hoc test performing comparisons in pairs to assess where there is significant difference.

3. RESULTS AND DISCUSSION

3.1. Pre-test

All subjects in the three groups used a monitor as display device, without any auxiliary lateral image, to execute a pick-and-place procedure with three levels of difficulty in the pre-test. The test results of mean task time and collision frequency are listed in Table II. It can be seen that both the mean task time and collision frequency increased with the level of difficulty. On the other hand, each group performed best at differing levels of difficulty. It is necessary to investigate further. ANOVA was employed to analyze whether the group factor made a difference. The results are listed in Table III. It was found that there was no significant difference ($p>0.05$) among the three groups' test results of mean task time and collision frequency at each difficulty level. This means that the way of assigning subjects randomly to various groups made no difference to outcomes among the three groups. Therefore, the three groups' subjects come from the same population.

3.2. Main test

After it was confirmed in the pre-test that no difference existed among the three groups, it was possible to study the effects of various display devices and the inclusion of an auxiliary lateral image on the system performance in the main test.

The test results of the mean task time and collision frequency, which the three groups took in each difficulty level with and without the help of an auxiliary lateral image, are listed in Table IV and Table V, respectively. It was found that on average, the three groups that executed the procedure with the help of an auxiliary lateral image spend more time than they did without the help of an auxiliary

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Table II. The average task time and collision frequency in pre-test.

	Average task time (ms)			Collision frequency		
	Low difficulty	Middle difficulty	High difficulty	Low difficulty	Middle difficulty	High difficulty
Projector group	3645.97 (3844.07)	4380.55 (2133.56)	6826.13 (4930.58)	1.21 (1.28)	2.76 (1.84)	3.92 (2.96)
Monitor group	4859.86 (5193.20)	4583.05 (2805.45)	8016.57 (6232.60)	1.05 (0.91)	2.19 (1.68)	4.41 (3.52)
HMD group	3942.92 (3165.18)	4846.38 (3200.59)	6465.98 (4587.00)	1.52 (1.26)	2.42 (1.50)	3.73 (2.23)

Note. Values enclosed in parentheses represent standard deviation.

lateral image, but the reverse appeared in the data of collision frequency. The results are reasonable, as these subjects may have used the extra time spent to adjust their hand position to avoid the collision between cylinder and hole. The auxiliary lateral image, which helped subjects to operate the VR-based hand rehabilitation system, is shown in Figure 1. In addition, the results show that on average, the performance of the projector group was the best in mean task time and collision frequency without access to any auxiliary lateral image, followed by the monitor group and the HMD group. However, in tests where an auxiliary image was used, the projector group was followed by the monitor group in its performance of collision frequency. The HMD group was almost always the last one in all tests.

Table III. ANOVA for the factor of group.

	Average task time			Collision frequency		
	Low difficulty	Middle difficulty	High difficulty	Low difficulty	Middle difficulty	High difficulty
P value	0.417	0.756	0.410	0.198	0.332	0.584

Table IV. Mean task time (ms) of the three groups in main test.

	With an auxiliary lateral image			Without an auxiliary lateral image		
	Low difficulty	Middle difficulty	High difficulty	Low difficulty	Middle difficulty	High difficulty
Projector group	2442.02 (1038.56)	3246.18 (2173.65)	4444.55 (2659.40)	2308.53 (908.22)	2670.05 (1419.38)	4382.37 (3784.41)
Monitor group	2673.85 (1242.20)	3340.43 (1485.52)	6104.37 (3755.38)	3241.08 (3869.98)	3580.55 (2143.38)	6079.48 (4633.04)
HMD group	3246.38 (1977.18)	4463.77 (3584.64)	7706.75 (8691.35)	2771.52 (1114.57)	3805.30 (2266.91)	6686.62 (5765.82)

Note. Values enclosed in parentheses represent standard deviation.

Table V. Collision frequency of the three groups in main test.

	With an auxiliary lateral image			Without an auxiliary lateral image		
	Low difficulty	Middle difficulty	High difficulty	Low difficulty	Middle difficulty	High difficulty
Projector group	0.83 (0.90)	1.90 (1.39)	2.95 (2.14)	1.27 (0.78)	2.00 (1.18)	3.05 (1.72)
Monitor group	0.62 (0.67)	1.83 (1.11)	2.65 (2.09)	1.10 (1.34)	2.20 (1.44)	3.77 (2.54)
HMD group	1.18 (1.28)	2.30 (1.45)	3.90 (2.57)	1.02 (0.97)	2.70 (2.29)	4.57 (3.25)

Note. Values enclosed in parentheses represent standard deviation.

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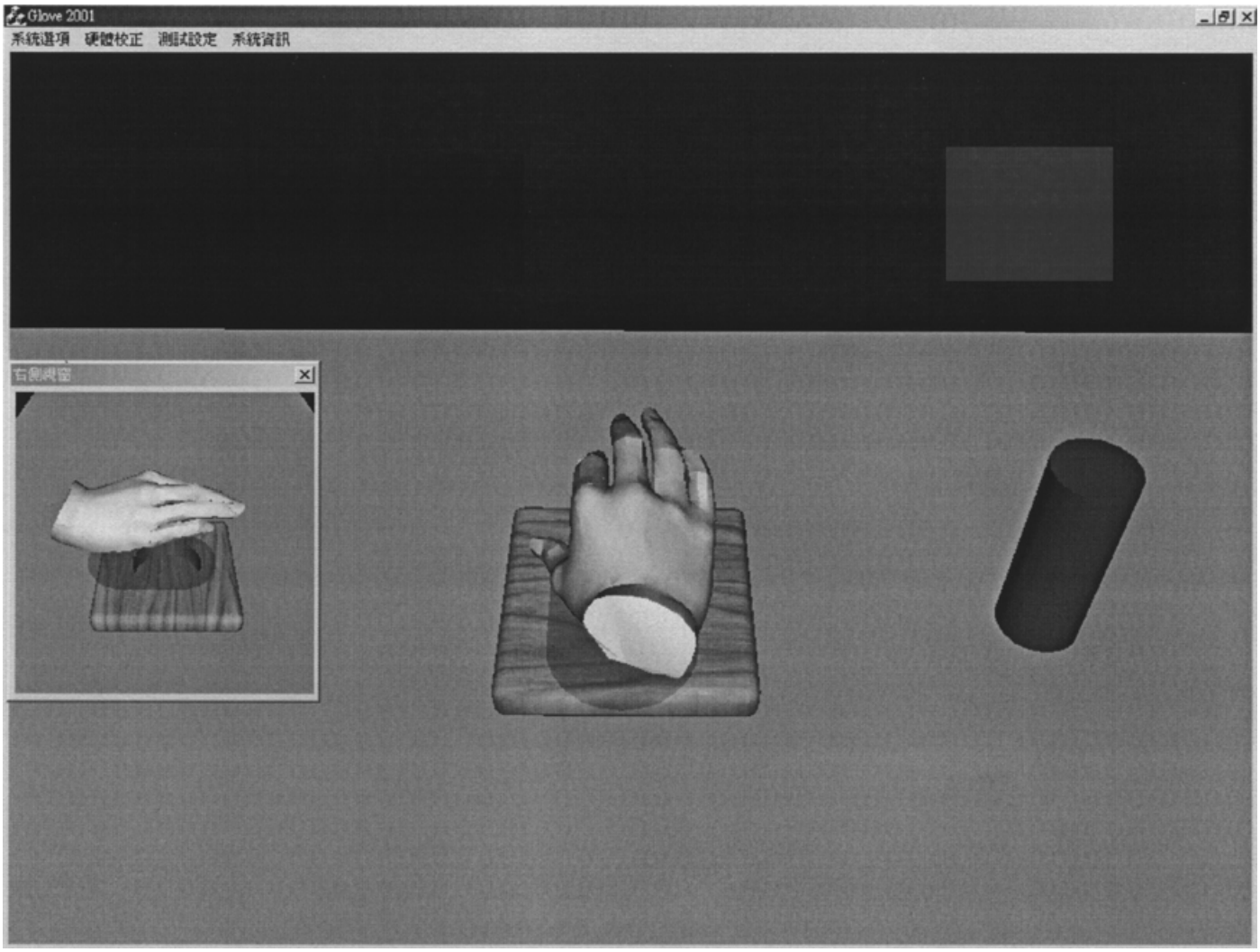

Fig. 1. The auxiliary lateral image which helped subjects to operate the VR-based hand rehabilitation system.

The test results shows that the projector group and the monitor group demonstrated their respective best performance under certain test conditions. However, it is a fairly rough observation on the test results. The real effect of various display devices on manipulation performance still needs to be investigated further using rigorous statistical methods. Before testing the performance of groups with different display devices, the effect of test sequence was investigated. The results of ANOVA on the test sequence are listed in Table VI. The results show that the test sequence was a significant factor ($p=0.003$) in the HMD group's collision frequency at the middle level of difficulty. In addition, it was almost a significant factor ($p=0.097$) for HMD group's mean task time at the middle level of difficulty. This indicates that the test sequence did affect the test results more or less at the middle level of difficulty for the HMD group. Subjects were able to gain some experiences of manipulating the system from the previous test. The effect of this prior experience could induce misjudged conclusion. Therefore, the test results at the middle level of difficulty have not been included in the following analyses.

In order to understand the effect of the auxiliary lateral image and display devices, a two-factor ANOVA was first made. The results of these effects are listed in Table VII. For the influence of an auxiliary lateral image, it can be seen that this factor had a significant effect ($p=0.045$) for

Table VI. ANOVA for the factor of test sequence.

	Average task time			Collision frequency		
	Low difficulty	Middle difficulty	High difficulty	Low difficulty	Middle difficulty	High difficulty
Projector group	0.610	0.247	0.634	0.581	0.584	0.950
Monitor group	0.499	0.798	0.562	0.261	0.319	0.244
HMD group	0.192	0.097	0.386	0.221	0.003*	0.350

* $p<0.05$.

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Table VII. A two-factor ANOVA for the auxiliary lateral image and display devices.

	Average task time		Collision frequency	
	Low difficulty	High difficulty	Low difficulty	High difficulty
Auxiliary lateral image	0.957	0.587	0.051	0.045*
Display devices	0.082	0.004*	0.301	0.003*
Auxiliary lateral image × display devices	0.240	0.794	0.092	0.411

* $p<0.05$.

collision frequency at the high difficulty level; and it was almost significant ($p=0.051$) for collision frequency at the low difficulty level. However, there was no significant effect on mean task time. This analysis result supports the statement about the observations of Table IV and Table V. With the help of an auxiliary lateral image, a reduction in collision frequency was statistically significant. On the other hand, the factor of display device showed a significant effect at the high difficulty level for both mean task time ($p=0.004$) and collision frequency ($p=0.003$). However, it was not significant at the low difficulty level. This means that the display device at the high level of difficulty is a significant factor, and the differences among test results from various display devices were significant.

In addition, Table VII shows that there was no interaction between the two factors since no significant effect was seen ($p>0.05$). Therefore, one-factor ANOVA can be further employed to investigate the respective effects of the auxiliary lateral image and display devices. The individual effect of the auxiliary lateral image can be seen in Table VIII. The auxiliary lateral image was a significant factor for the projector group-and the monitor group in collision frequency. It did not make any difference for the HMD group ($p>0.05$). Therefore, it is understood that the result of statistical analysis from Table VII (i.e. the auxiliary lateral image) which showed a significant effect on collision frequency, was caused by the projector group and the monitor group.

Table VIII. One-factor ANOVA for the auxiliary lateral image.

	Average task time		Collision frequency	
	Low difficulty	High difficulty	Low difficulty	High difficulty
Projector group	0.542	0.932	0.020*	0.818
Monitor group	0.380	0.979	0.048*	0.034*
HMD group	0.190	0.538	0.557	0.306

* $p<0.05$.

The effect of various display devices on the performance of manipulation was also studied using one-factor ANOVA for the condition of with or without an auxiliary lateral image. The results are listed in Table IX. The data indicate that the factor of display device was significant ($p<0.05$) in all conditions with an auxiliary lateral image. Even without an auxiliary lateral image, the factor of display device was also significant for collision frequency at the high difficulty level ($p=0.033$) and nearly significant for mean task time at the high difficulty level ($p=0.088$). Therefore, performance difference among various display devices was statistically significant in most conditions. However, it was not clear yet which difference between the two groups was the cause for difference in significance. To understand this question, it was necessary to make a comparison in pairs. The Tukey test was employed to compare performance difference between two groups in pairs. The results, listed in Table X, show that without an auxiliary lateral image, the performance difference between the projector group and the HMD group was significant ($p=0.025$), and that the performance difference between the monitor group and the HMD group was nearly significant ($p=0.085$). Therefore, it can be understood these two differences (i.e. projector-HMD and monitor-HMD) made statistically significant differences, as seen in Table IV, at the high difficulty level without an auxiliary lateral image. In addition, significant differences were also found in the comparisons of the projector-HMD and the monitor-HMD for the conditions with an auxiliary lateral image. Again, these two differences made statistically significant differences, as seen in Table IV, in the conditions without an auxiliary lateral image. On the other hand, no statistically significant difference was found in the comparison between the projector group and the monitor group in any test condition. This means that no difference

Table IX. One-factor ANOVA for the display devices.

	Average task time		Collision frequency	
	Low difficulty	High difficulty	Low difficulty	High difficulty
With an auxiliary lateral image	0.047*	0.040*	0.044*	0.041*
Without an auxiliary lateral image	0.221	0.088	0.556	0.033*

* $p<0.05$.

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Table X. The Tukey test between two groups in pairs.

	With an auxiliary lateral image			Without an auxiliary lateral image		
	Projector-Monitor	Projector-HMD	Monitor-HMD	Projector-Monitor	Projector-HMD	Monitor-HMD
Low difficulty task time	0.762	0.043*	0.196	0.191	0.661	0.653
High difficulty task time	0.394	0.031*	0.419	0.257	0.838	0.085
Low difficulty collision frequency	0.662	0.285	0.047*	0.740	0.542	0.946
High difficulty collision frequency	0.826	0.153	0.041*	0.422	0.025*	0.351

* $p<0.05$.

was demonstrated between manipulation performances using the projector or the monitor as a display device.

4. CONCLUSION

To assess the effect of an auxiliary lateral image and display devices on manipulation performance in a virtual reality-based hand rehabilitation system, twelve healthy, non-disabled right-handed volunteers were recruited to participate in a hand-eye coordination test with different levels of difficulty. The results are as follows.

(i) On average, three groups executing the procedure with the help of an auxiliary lateral image spend more time on it than they did without its help. However, a reverse result appeared in the data of collision frequency. In addition, the projector group and the monitor group carried out their respective best performance in differing test conditions.

(ii) The presence of an auxiliary lateral image was a significant factor for the projector group and the monitor group in collision frequency. It did not make any statistical difference for the HMD group. Therefore, the auxiliary lateral image was not necessary to enhance the performance of the HMD group.

(iii) No statistically significant difference was found in the comparison between the projector group and the monitor group in any test condition. This means that there was no difference in manipulation performances which involved using either the projector or the monitor as a display device. Statistical difference was only found in the comparison between the projector group (or monitor group) and the HMD group.

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