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The study of auditory and haptic signals in a virtual reality-based hand rehabilitation system

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SUMMARY
The purpose of the present study is to assess the influence of auditory and haptic signals on the manipulation performance in a virtual reality-based hand rehabilitation system. A personal computer, a tracker, and a data glove were included in this system. Three-dimensional virtual environments were developed. Forty volunteers were recruited to participate in a pick-and-place procedure, with three levels of difficulty and four feedback modes. Task time and collision frequency were the parameters used to evaluate their manipulation performance. It can be concluded that the haptics is a significant signal for improving a subject's performance at the high difficulty level.

KEYWORDS: Virtual reality; Hand rehabilitation; Haptic signals.

1. INTRODUCTION
Patients who have been disabled following accidents or surgery usually undergo long-term rehabilitation therapy which is designed to restore some of their lost sensory perception. However, long-term therapy involves spending a lot of money on medical care and available resources at a given clinic, and may also be insufficient as the number of patients needing rehabilitation has increased over time. The reduction of therapy duration could be a solution, but it would have a negative effect on the patient's condition and worsen it. Currently, patients needing rehabilitation exercises must repeatedly visit specialized clinics or hospitals. If a simple personal rehabilitation system with adequate therapeutic intervention for patients could be done at home, following an initial assessment at the clinic, it would help patients return early to their normal lives and social interaction and thus reduce the societal cost.

Clinical evaluation of a patient hand disability can be difficult and inaccurate because of the complexity of the hand's anatomy. To overcome the limitations of traditional hand function diagnosis and rehabilitation instruments, computer-based hand diagnosis and rehabilitation systems, such as Eval,[1], Clinical Hand Master[2] and Dexter,[3] were developed with the capability of online data collection. The instruments described above can execute data acquisition and analysis. However, virtual reality technology has not yet been applied to their proposed systems yet. Virtual reality (VR) is a computer graphic technology. It can be used to create fictitious objects and events that simulate a realistic, three-dimensional scene and allow segments of a scenario to be manipulated.[4,5] In the field of medicine, a great variety of VR applications have been developed, ranging from operational illusory training to remote telepresence surgery.[6,7] Virtual rehabilitation exercise is one VR application to attract the physician's interest. In particular, hand-eye coordination testing is an important aspect of the hand disability treatment process. The VR-based hand-eye coordination test could make patients more willing to participate and immerse themselves in the virtual environment than can be the case with the replicating exercises routinely carried out in the rehabilitation clinics.

Burdea and his colleagues[8,9] were the first to develop a hand rehabilitation system using VR simulation technology. Their system includes a Pentium II personal computer (PC) with a graphics accelerator, a polhemus tracker, and a multipurpose haptic control interface, sampling patient hand positions. The resistive force is provided by the Rutgers Master II glove. The system has some benefits in clinical practice and at-home exercises.

As well as the sensing glove system used for hand diagnosis and rehabilitation, Prisco[10] developed an immersed virtual environment which provided visual, auditory and haptic feedback, designed specifically to help to recover or improve the motor dexterity of the patient arm and hand. Based on robot and virtual reality technology, Sakaguchi[11] developed a rehabilitation training system using electro-rheological actuators. Such systems can help patients in rehabilitation training so that fewer therapists are needed and training can be more enjoyable than traditional systems.

Most VR-based hand rehabilitation systems have provided visual and auditory signals to help user receive information. As for the haptic signal, it is not often incorporated in these systems owing to its complex technologies and high cost. "Haptics" refers to the sense of touch[12] and it involves tactile and force feedback perception. It is believed that the use of haptics will become widespread

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in the future as the technology difficulties are overcome and hardware price is reduced. However, the system developers still face a question that whether or not the haptic signal is really helpful for users in performance, and whether users feel that it is realistic and easy to manipulate, making it worthwhile to develop.

Some research has been undertaken to understand the role of feedback signal in hand rehabilitation. Howe and Kontarinis[13] investigated the benefits of haptics in a two-dimensional peg-insertion task and they found that with force feedback, participants completed the task in less time than with only visual feedback. In another study,[14] a pick-and-place experiment also found similarly that haptics could improve task completion time by 30%. On the other hand, Massimino and Sheridan[15] found equal performance with or without force feedback, in their study of a two dimensional peg insertion task.

The purpose of the present study is to assess the influence of auditory and haptic signals on the manipulation performance in a virtual reality-based hand rehabilitation system. A personal computer, a tracker, and a data glove were included in the system. Three-dimensional virtual environments were developed using the *V*irtual *R*eality *M*odeling *L*anguage (*VRML*). All the paths of hand motion were recorded and stored in a computer. To assess the influence of auditory and haptic signals in a virtual reality-based hand rehabilitation system, forty healthy, non-disabled right-handed volunteers ranging from 20 to 25 years old were recruited. The test was a pick-and-place procedure, with three levels of difficulty and four feedback modes. Task time and collision frequency were the parameters used to evaluate the subject's manipulation performance. The results of average task time and collision frequency were analyzed using statistical methods to assess the influence of various levels of difficulty and feedback signals.

2. METHOD AND MATERIAL

2.1. Subjects

The subjects recruited for this study were forty right-handed male volunteers with a mean age of 22.5 ± 2.5, ranging from 20 to 25 years old. The first ten participants were tested in the pilot test and the other thirty participants took the main test. The subjects were presumed healthy and non-disabled because none reported any history of neuromuscular, metabolic or ophthalmic disease. The experimental procedures were approved by the local institutional review board for human research and adhered to the Occupational Health and Safety Administration regulations. Each subject had to give his informed consent to participating in this experiment.

2.2. System configuration

The VR-based hand rehabilitation system includes a data glove, a position tracker, a personal computer and three-dimensional virtual environments (VE). As the user put on the data glove, the motions of hand can be simulated and they appeared in the VE. In addition, the operating dynamic data, such as hand position coordinates and finger-bending angles, were recorded and stored into a personal computer.

The data glove used to measure a finger bending extent was a 5DT Data Glove, produced by iReality.com, Inc.[16] Each finger of the data glove has a fiber-optic bend sensor. One end of each fiber is connected to a Light Emitted Diode (LED), and the other end is a phototransistor receiving light from the LED. Less light arrives at the phototransistor when the finger is bent. Accordingly, the amount of light detected depends on the extent of finger bending. In this way the joint angle of the finger is measured. The sensitivity, accuracy and update rate of the data glove are 1 degree, 5.6 degree and 60 Hz, respectively.

The position tracker used in the system is Fastrak[17] from the Polhimus Company. The Fastrak is a magnetic sensor that employs alternating low-frequency fields generated by a transmitter, to determine the moving object position and orientation. To measure hand motion, a receiver is placed on the back of the user sensing glove. The position coordinates are transferred into PC through RS-232 and the data update rate is up to 120 Hz, which is fast enough to catch the motion of the data glove.

The virtual environment is based on the pick-and-place task, in which the patient picks a peg and places it into a hole. The 3D objects are constructed using VRML. The object behaviors and VE software are programmed using VC++ language. Finally, the virtual scene is displayed through ComsoPlayer ActiveX on a desktop Pentium III PC platform with a 15″ Liquid Crystal Display (LCD) screen showing excellent image quality.

2.3. Procedures

The experimental tools for the pick-and-place test were located on a table. The subject was asked to sit comfortably on a chair and hold his arm outstretched in front of him, as shown in Figure 1. His forearm rested in a neutral position, with the data glove fitted in the right hand.

Before the study, the examiner explained the test requirements to each subject and answered questions. The subject was then asked to transfer a cylinder from its original field to the target hole. Each subject needed to grasp

Fig. 1. The subject manipulates the virtual reality system.

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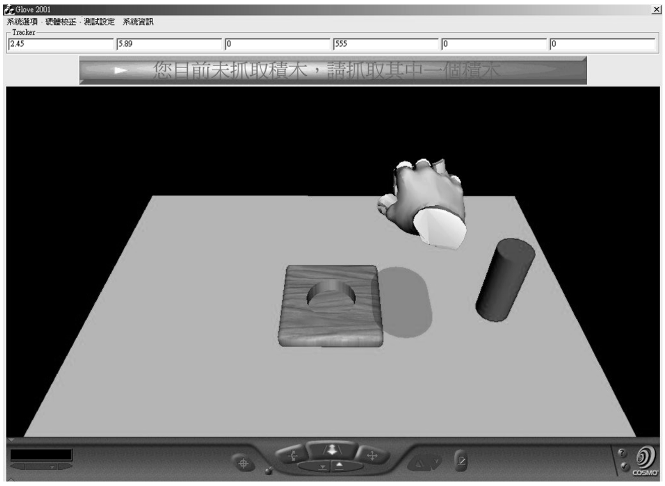

Fig. 2. A VR display shows how the illusory hand approaches and grasps the objects.

the cylinder first and then move it from right to left into the target hole as quickly as possible. The process in which that illusory hand approached and grasped the object is shown in Figure 2.

Three levels of difficulty, listed in the Table I, for the pick-and-place test were designed for the present study. The task difficulty was assessed using Fitts' law[18] according to various cylinder diameters and hole-cylinder distances:

$$I_d = LOG_2[2*A/(D_h - D_p)] \quad (1)$$

where A: the distance traveled, D_h: the diameter of the hole, and D_p: the diameter of the peg.

2.4. Experimental design and measures

One pilot test was conducted to determine how many trials were required to obtain a steady performance of the pick-and-place test, with nofeed back, at three levels of difficulty.

In each trial, task time (the period of time in seconds from grasping the object to releasing it) and collision frequency (the number of collisions between object and hole) were recorded. Also, the data shows that the spatial hand motion paths projected onto the vertical plane facing the subject (the x-y plane of the three-dimensional rectangular coordinate system) are curved, fitting a second order polynomial to obtain the coefficient of determination (R^2).

The main test is designed to a $2\times2\times3\times4$ within study with four factors. The first factor is sound and the second factor is haptics. The first factor constitutes the feedback mode with or without sound. The second factor constitutes the feedback mode with or without haptics. Therefore, the first two factors constitute four collision feedback modes. They are: no feedback, feedback with sound signal, feedback with haptic signal, and feedback with sound and haptic signals. The third factor involves the difficulty indices.

The fourth factor is order. The order of presentation of the four collision feedback modes was determined by three balanced Latin squares, providing twelve different orders of presentation. Thirty participants were randomly assigned to one of the presentation orders prior to their arrival.

The effects of four collision feedback modes and three difficulty indices on the system performance were studied. Each subject was asked to do a practice session for each feedback mode and each level of difficulty before the formal task. The formal pick-and-place task was undertaken four times (4 trials) for each feedback mode and difficulty index. In each trial, the task time and collision frequency were recorded.

Table I. Three levels of difficulty designed in the present study.

Level of difficulty	A (cm)	D_h (cm)	D_p (cm)	I_d
Low	10	3.0	2	4.322
Middle	10	2.5	2	5.322
High	10	2.3	2	6.060

2.5. Statistical methods

The results of average task times in main tests were analyzed using a four-factor (sound, haptics, level of difficulty, and order) analysis of variance (ANOVA). The data were also analyzed separately for each level of difficulty with a two-factor (sound and haptics) analysis of variance.

As the data of collision frequency were non-continuous and non-normally distributed, they were analyzed using nonparametric tests. Wilcoxon Sign-rank test and Kruskal-Wallis test were employed here. The resulting achievement of a probability level smaller than 0.05 ($p<0.05$) was considered as statistically significant.

3. RESULTS AND DISCUSSION

3.1. Reliability

To determine how many trials were required to obtain a steady performance of the pick-and-place test at three different levels of difficulty, the procedure was repeatedly undertaken with no feedback. The average task time of ten subjects for each trial is shown in Figure 3. It can be seen that the average task time in the first trial was longer than that in the following trials. Also, the task time decreased as the practicing frequency increased, reaching a stable

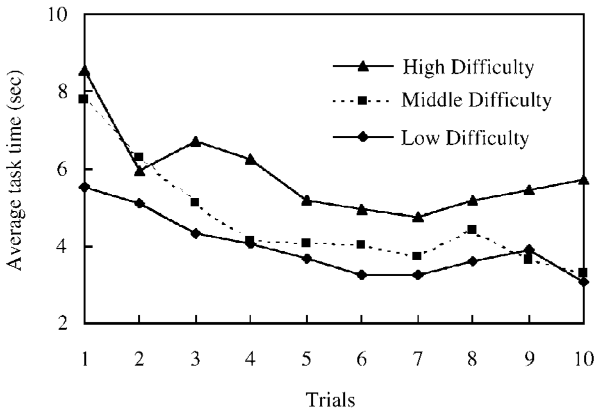

Fig. 3. The average task time of ten subjects for each trial with no feedback.

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requiring time after the fourth trial. The trend is reasonable and it means that an ordinary person would need about four trials of practice frequency to get used to the virtual environment in the experiment.

The position of the receiver on the subject wrist was measured by the magnetic transmitter which was placed on the table, and was determined by the rectangular coordination system, (x, y, z), of the virtual reality. In this study, the leftward or rightward movement of the hand was defined to be the X-axis value. The up or down movement of the hand was defined to be the Y-axis value and was measured from the table surface. The Z-axis laid on the horizontal plane represented the back and forth movements of the hand.

Raw position data in x, y, and z coordinates were used to reconstruct spatial hand motion paths. Using VRML, these paths have been displayed in real time to show the kinematics features of the paths of the wrist joint. Figure 4 shows a typical spatial hand motion path from an experienced subject. It can be seen that the path is nearly a parabola. In fact, all the experimental results show the same trend. The trend could be considered a typical hand behavior model for all the subjects. Accordingly, the projection of the spatial path on the vertical plane facing the subject (x-y plane) can be represented by a polynomial. Using the least square method, the second order polynomial can be obtained as follows:

$$\hat{Y} = aX^2 + bX + c \qquad (2)$$

The coefficient of determination (R^2), based on the motion path projected on the XY plane, could be calculated as follows:

$$R^2 = \frac{\Sigma(\hat{Y} - \bar{Y})^2}{\Sigma(Y - \bar{Y})^2} \qquad (3)$$

where $\bar{Y}$ is the mean of all values of Y in test data. The test data were sampled every two microseconds. Generally, with more experience on the pick-and-place procedure and the VR system, the projection of the spatial path on the x-y plane was closer to a second order polynomial, the R^2 becoming stable. Accordingly, the variance of R^2 is used as an index to determine the number of trials required to obtain a steady performance of the test.

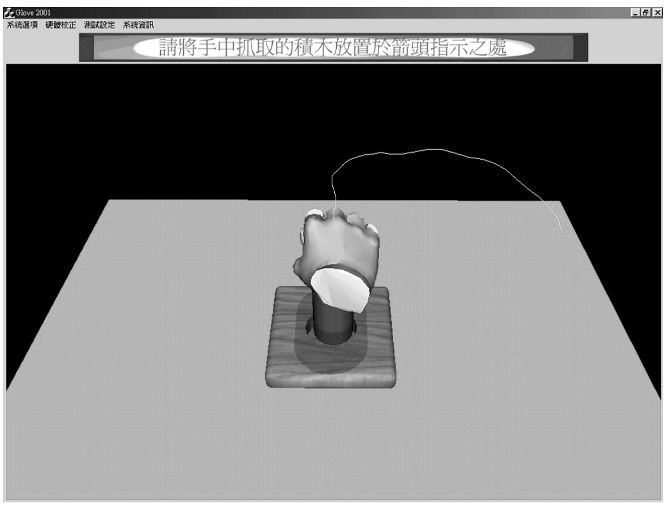

Fig. 4. A typical spatial hand motion path by an experienced subject.

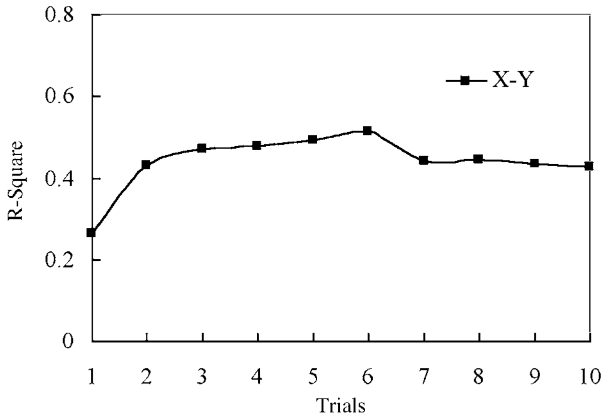

Fig. 5. The average value of R^2 for all ten subjects at each trial.

Figure 5 shows the average value of R^2 for all ten subjects at each trial. It can be seen that R^2 value increased with the trial frequency in the first few trials. After four trials, the R^2 is stable and this phenomenon agrees with the result in the task time. With an experienced subject, the experimental result itself could be repeated, thus, the system reliability was acceptable.

3.2. *Effect of difficulty index*

The effect of difficulty on the task time can be observed in Figure 6. The average task time increases with the difficulty index. It is understood that the difficulty index depends on the difference between the diameters of the hole and the peg. The smaller the difference, the more difficult the test is. Subjects will take more time to finish the test. Accordingly, it provides a reference for the design of a therapy procedure to keep the subject's interest and confidence in using the VR system.

Figure 6 also shows that the task time decreased sharply as the trials frequency increased, and became stable after the fourth trial for the middle and low difficulty indices. Therefore, the first four trials can be treated as practices in which the subjects familiarize themselves with the test process and the VR system. However, the task time after four trials still had a large variation for the high difficulty index. This shows that the performance of the subjects was

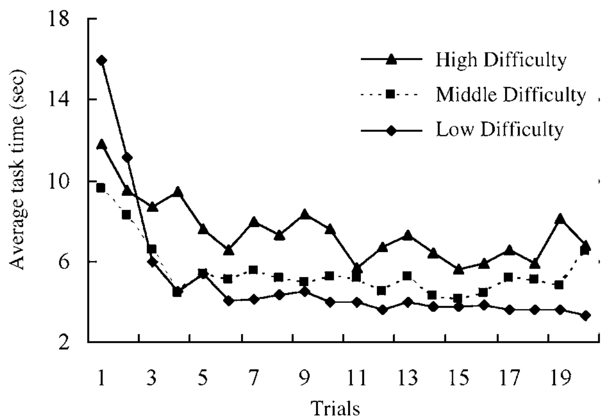

Fig. 6. The effect of difficulty index on the task time.

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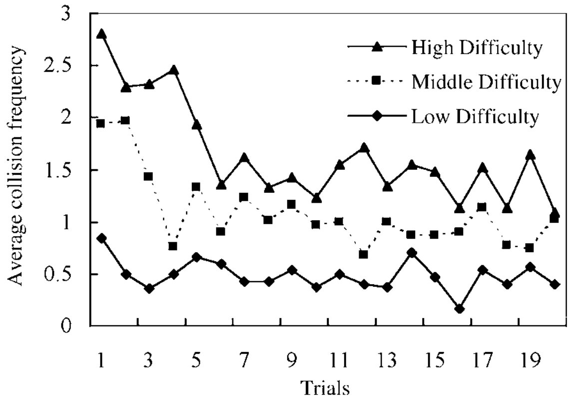

Fig. 7. The effect of difficulty index on the collision frequency.

still very unstable no matter how many trials they took. Therefore, the high difficulty index test may have been too difficult for the subjects.

Hand stability can be assessed by counting the number of collisions between the peg and hole. The effect of difficulty index on the collision frequency is shown in Figure 7. It can be observed that the collision frequency increased with the difficulty index (the difficulty of the test is indicated by the difficulty index). The smaller the difference of diameters between the peg and hole, the more difficult the test is. Therefore, collisions happened more frequently. In addition, the high collision frequency in the first few trials also indicates that the subjects needed to practice before their performances became stable.

3.2.2. Effect of feedback mode. Generally, when the collision happens, the VR system will remind the subject, with some kind of feedback mode, to correct his/her motion path. In the present study, four feedback modes (no feedback, feedback with sound signal, feedback with haptic signal, as well as feedback with sound and haptic signals) were proposed. The effect of feedback mode on the task time is shown in Figure 8. It can be seen that task time was not very much affected by the feedback mode for the tests at the level of middle and low difficulty indexes. However, Figure 8 shows a strong influence from the feedback mode on the task time in the high difficulty index test. In the four feedback modes, the feedback with sound can help the subjects to achieve a shorter task time. The feedback with both sound and text can reduce task time a little more than does the feedback with sound. But, the difference is not very obvious. Therefore, it can be understood that sound is a very good feedback mode in the VR system. In fact, the feedback with text is the easiest mode for the VR system with something-extra feedback, but it takes up the most task time. It can be attributed to the subject's spending some more time to read the information shown on the screen; it results in a longer task time than other modes do.

The test results of mean task time and collision frequency for the different levels of difficulty and feedback modes are listed in Table II. It shows that at all levels of difficulty, both mean task time and collision frequency are reduced with the help of feedback. But, whether or not the reduction is statistically significant, or at least a small magnitude effect is induced by the effect of feedback, this is needed to be investigated further using statistical methods.

Task time and collision frequency are related to each other in the scatter plot of Figure 9. The correlation coefficient r=0.634. It shows a close positive correlation between the task time and collision frequency.

Table II. Mean task time and mean collision frequency.

Level of difficulty	Feedback condition	Mean task time (ms)	Mean collision frequency
All	None	4511.92	2.16
	Sound	4272.62	2.13
	Haptics	4215.67	1.91
	Sound and haptics	4055.20	1.94
Low	None	3366.46	0.93
	Sound	3330.43	1.06
	Haptics	3291.22	0.94
	Sound and haptics	3170.53	0.79
Middle	None	4016.06	2.10
	Sound	3784.36	2.05
	Haptics	3829.85	1.93
	Sound and haptics	3916.21	2.22
High	None	6153.25	3.46
	Sound	5703.07	3.29
	Haptics	5526.30	2.86
	Sound and haptics	5078.86	2.82

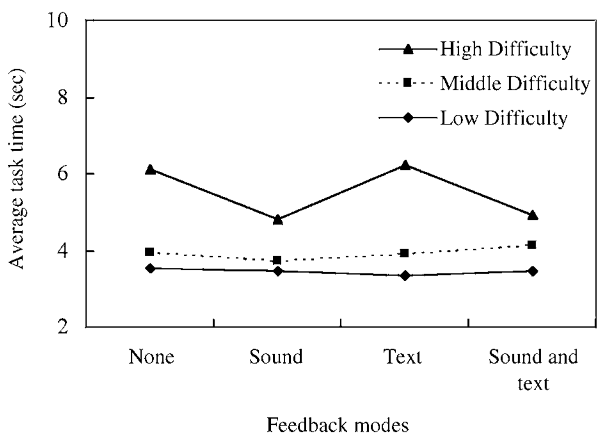

Fig. 8. Average task time for different feedback modes with different difficulty indices.

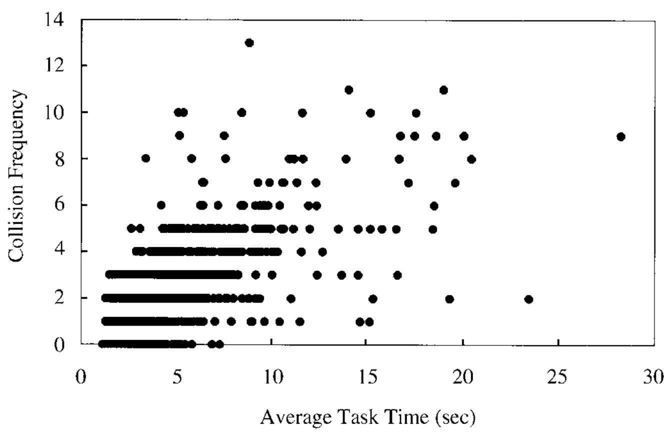

Fig. 9. The scatter diagram of average task time and collision frequency.

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Table III. Four-way ANOVA of task time.

	Degree of freedom	Mean square	F value	P value
Sound (y/n)	1	12951836.1	1.933	0.165
Haptics (y/n)	1	22580408.7	3.370	0.067
Level of difficulty	2	678033515.5	101.195	0.000
Order	3	7890317.5	1.178	0.317
Sound × Haptics	1	513862.9	0.077	0.782
Sound × Level of difficulty	2	4855376.4	0.725	0.485
Haptics × Level of difficulty	2	11726065.7	1.750	0.174
Sound × Haptics × Level of difficulty	2	1311420.6	0.196	0.822

In order to understand the effect of feedback mode, difficulty index and test order on the task time of experiment, a four-factor ANOVA was made. The results are listed in Table III. The data indicate that the level of difficulty had a significant effect ($p=0.000$). There was no significant effect for sound ($p=0.165$) and order ($p=0.317$). As for the factor of haptics, the p-value equaled 0.067. Since it was larger than 0.05, it was not defined as a significant effect, in the present study, on the task time. However, it was still quite significant.

The data also indicate that there was no significant effect for the interactions between the level of difficulty and whatever feedback mode, although the level of difficulty showed a significant effect. The results shown in Figure 10(a), Figure 10(b), and Figure 10(c) can explain it more detail. There is no intersection between the two data lines for cases with and without feedback. It can be also seen that the task time differences between the two modes of with and without feedback increased with the level of difficulty. The task time differences were further analyzed using a two-factor ANOVA separately for each level of difficulty. The results are listed in Table IV, Table V, and Table VI. A significant effect ($p=0.080$) was found for haptics at the high level of difficulty, but no significant difference emerged at the middle and low level of difficulty ($p=0.879$, and $p=0.348$). On the other hand, Table III shows the level of difficulty had a significant effect, and the effect of haptics came very close to the definition of significance. Therefore, it can be concluded that the factor of haptics played an important role in task time analysis, and the higher level of difficulty was the more significant the effect.

The data of collision frequency were examined using the Wilcoxon Sign-rank test to understand the difference between with feedback and without feedback in the VR

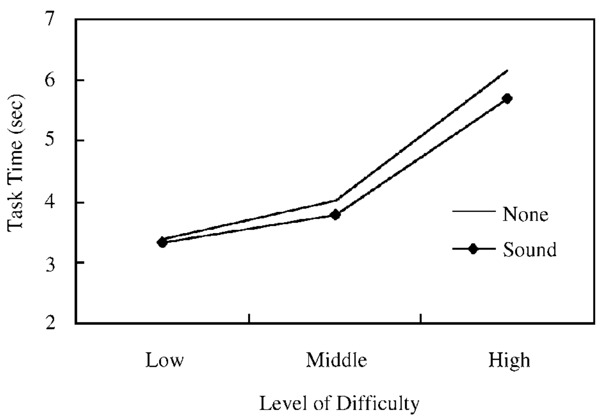

Fig. 10a. The interaction between sound signal and level of difficulty.

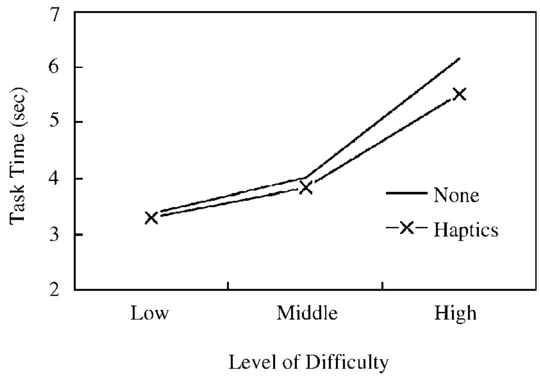

Fig. 10b. The interaction between the haptic signal and level of difficulty.

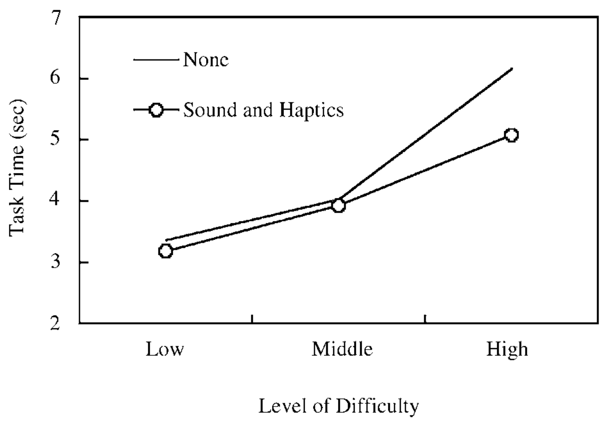

Fig. 10c. The interaction between the sound × haptic signal and level of difficulty.

Table IV. Three-way ANOVA of task time for a low level of difficulty.

	Degree of freedom	Mean square	F value	P value
Sound (y/n)	1	696776.91	0.379	0.538
Haptics (y/n)	1	1623612.56	0.883	0.348
Sound × Haptics	1	291301.51	0.158	0.691

Table V. Three-way ANOVA of task time for a middle level of difficulty.

	Degree of freedom	Mean square	F value	P value
Sound (y/n)	1	603306.31	0.157	0.692
Haptics (y/n)	1	89403.53	0.023	0.879
Sound × Haptics	1	2835933.86	0.738	0.391

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Table VI. Three-way ANOVA of task time for a high level of difficulty.

	Degree of freedom	Mean square	F value	P value
Sound (y/n)	1	21362505.79	1.481	0.224
Haptics (y/n)	1	44319523.98	3.073	0.080
Sound × Haptics	1	9468.80	0.001	0.980

based pick-and-place procedure. The results are listed in Table VII. It was found that haptics at the high level of difficulty (p=0.021) was a significant factor. This means that feedback with haptics can really help the VR based pick-and-place procedure at the high level of difficulty to avoid collisions. On the other hand, no significant effect was found for feedbacks with haptics at the lower difficult level, nor for feedbacks with sound at all difficult levels. This conclusion is logical since the study of task time in previous section shows that the factor of haptics plays an important role in the high level of difficulty, and the plot of Figure 9 shows a close positive correlation between the task time and collision frequency.

The Kruskal-Wallis test was employed to study interactions for each level of difficulty on four feedback modes. Table VIII shows the results. No significant difference was found. However, if the data are further analyzed for any difference between two feedback modes separately at each level of difficulty (Tables IX, X, and XI), it can be seen that the difference between no feedback and feedback with sound and haptics was significant (p=0.03) at the high level of difficulty. This is reasonable since the task time difference between the two modes, as shown in Figure 10(c), was also obvious at the high level of difficulty.

The Kruskal-Wallis test results also indicate a significant difference (p=0.000) among different levels of difficulty in

Table VII. The Wilcoxon Sign-rank test of collision frequency.

Feedback/ Level of difficulty	Mean collision frequency: with feedback	Mean collision frequency: without feedback	P value
Sound/Low	0.922747	0.939914	0.798
Haptics/Low	0.866953	0.995708	0.223
Sound/Middle	2.137339	2.025751	0.523
Haptics/Middle	2.085837	2.077253	0.919
Sound/High	3.051502	3.163090	0.266
Haptics/High	2.841202	3.373391	0.021

Table VIII. The Kruskal-Wallis test of collision frequency.

Level of difficulty	Feedback mode: None	Sound	Haptics	Sound and haptics	P value
Low	0.93	1.06	0.94	0.79	0.385
Middle	2.10	2.05	1.93	2.22	0.709
High	3.46	3.29	2.86	2.82	0.182

Table IX. P values of the Kruskal-Wallis test for collision frequency at a low level of difficulty.

	None	Sound	Haptics	Sound and haptics
None	–	0.263	0.673	0.572
Sound	–	–	0.453	0.083
Haptics	–	–	–	0.306
Sound and haptics	–	–	–	–

each feedback mode, as listed in Table XII. This means that the results of collision frequency were statistically significant in different levels of difficulty. Also, the results in Table VII indicate that haptics at the high level of difficulty was a significant factor. Therefore, it can be concluded from the collision frequency analysis, that the factor of haptics played an important role at the high level of difficulty and that the results at different levels of difficulty show a significant difference.

4. CONCLUSION

To assess the influence of various levels of difficulty and feedback signals in the VR-based hand rehabilitation system, forty healthy volunteers were recruited to participate in a hand-eye coordination test which contained three levels of difficulty and four feedback signals. The results are as follows.

(i) The present study has shown that a person normally needs at least four practice attempts to get used to the virtual environment in the experiment. After that, the experiment is reproduced very well. Accordingly, the system's reliability is acceptable.
(ii) In the present study the level of difficulty had a significant effect on the task time. Both sound and order had no significant effects. The effect of haptics was very close to the definition of significance. However, when task time differences were further analyzed separately for each level of difficulty, haptics produced a significant effect at the high level of difficulty.
(iii) The results of collision frequency are seen as statistically significant at different levels of difficulty. Statistical analysis of collision frequency also indicates that haptics at the high level of difficulty is a significant factor.
(iv) From both task time and collision frequency analysis, it can be concluded that feedback with haptics can really

Table X. P values of the Kruskal–Wallis test for collision frequency at a middle level of difficulty.

	None	Sound	Haptics	Sound and haptics
None	–	0.961	0.601	0.585
Sound	–	–	0.629	0.559
Haptics	–	–	–	0.274
Sound and haptics	–	–	–	–

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Table XI. P values of the Kruskal-Wallis test for collision frequency at a high level of difficulty.

	None	Sound	Haptics	Sound and haptics
None	–	0.413	0.084	0.030
Sound	–	–	0.395	0.167
Haptics	–	–	–	0.552
Sound and haptics	–	–	–	–

Table XII. The Kruskal–Wallis test of collision frequency.

	Level of difficulty			
Feedback	Low	Middle	High	P value
None	0.93	2.10	3.46	0.000
Sound	1.06	2.05	3.29	0.000
Haptics	0.94	1.93	2.86	0.000
Sound and haptics	0.79	2.22	2.82	0.000

enhance performance in a VR based pick-and-place procedure at the high level of difficulty.

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