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Evaluation of usability improvement of contactless human interface with visual, auditory, and tactile sensation for aerial display

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Abstract

We revealed the optimal feedback parameters of visual, auditory, and tactile modalities in the operation of aerial display and determined that aerial display could be further improved for use of as a contactless human interface by multimodal feedback combining these parameters. We proposed applying a vibration motor to the sole of the foot instead of fingertips to provide vibration as tactile feedback to operate the aerial display. Sensory evaluation tests were carried out to evaluate the optimal feedback parameters for operating the aerial display in three senses: visual (image change); auditory (touch tone); and tactile (vibration), and to evaluate the effect on the operation with a combination of these parameters. We analyzed the variance of the experimental data using Scheffé's method for obtaining significance levels of paired comparisons. We found that the combination of two or three modalities rather than only a single modality makes the aerial display easy to operate.

Keywords Aerial display · Contactless · Tactile · Multimodal

1 Introduction

Aerial images are expected to be used for signage and for road sign displays in automobiles, and various methods of forming aerial image have been proposed [1–4]. In recent years, aerial display as a contactless human interface has been attracting attention due to the influence of the COVID-19 pandemic. However, in aerial display, users do not experience the same tactile sensation of touching a screen as when operating a conventional touch panel since they touch an aerial image that is a screen floating in the air. In addition, without visual and auditory feedback, such as that provided by touch panel operation at ATMs, users do not feel that they are operating the aerial display, which reduces usability.

Previous studies reported methods for providing direct tactile feedback to the fingertips using ultrasonic waves or air jets [5–10], but these methods are somewhat complicated. Furthermore, the tactile feedback devices would be placed in the field of view looking at the aerial image. To address this problem, we consider that it is not necessary to provide tactile feedback directly to the fingertips for the user to recognize that he/she is touching the aerial image, so we focused on a method to provide tactile feedback to a different area of the body where it is easy to provide vibration using a vibration motor. Since this can be easily accomplished by simply attaching a vibration motor on the floor, we decided to provide tactile feedback to the sole of the foot in this study and conducted preliminary experiments to confirm the effectiveness of vibration to the sole of the foot. This method is expected not only to provide tactile feedback but also to be easy and inexpensive to implement.

We confirmed the improvement on usability of an aerial display in three senses: tactile feedback by vibration to the sole of the foot using a vibration motor; visual feedback using aerial image changes; and auditory feedback using sound. Specifically, we presented various types of feedback in each sense and revealed the optimal feedback parameters for the operation of the aerial display. Previous studies have reported that multimodal feedback combining visual,

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auditory, and tactile sensation is effective for touch panel operation, warnings while driving, and virtual reality (VR) systems [11–15]. We evaluated whether multimodal feedback makes aerial display operation easier than unimodal feedback by conducting an experiment with combinations of each optimal feedback parameter.

2 Experiment preparations

2.1 Overview of experimental apparatus

Figure 1 shows an overview of the experimental apparatus. We used Fresnel lens to display the aerial images in this study. The Fresnel lens displays the image in the air via a liquid crystal display (LCD), and the subject observed it as an aerial image. When the subject touched the aerial image, infrared sensors detected his/her finger. Arduino, which sends a signal to vibrate the vibration motor located on the sole of the subject's foot. The Arduino also sent signal to the PC, which switches the image and outputs a touch tone.

The aerial image was displayed with numbers and symbols arranged in four rows and three columns, as shown in Fig. 2.

2.2 Method to detect finger position

Figure 3 shows how the finger position is detected. Infrared LED arrays, one each on the left and bottom of the device, emitted infrared rays in a rightward and upward direction. We installed seven infrared sensors opposite these arrays: three on the upper and four on the right side of the device. On standby, all infrared sensors were always in a state of receiving infrared light. When a subject's finger reached the position of the aerial image of a certain number, specific infrared sensors stopped receiving infrared light and read the number that is pressed. The system then provided sensory feedback of image switching, touch tone, and vibration.

Fig. 2 Aerial image

2.3 Visual feedback (Experiment 1)

We provided visual feedback by switching the aerial image. The image shown in Fig. 2 changed simultaneously when the subject touched the aerial image. We compared five images, including no visual feedback. The types of changed images are shown in Fig. 4 (a), (b), and (c) and Fig. 5. Figure 4 shows (a) color (black and white) inversion of the pressed number, (b) color inversion of the non-pressed number, and (c) delete non-pressed numbers. The changed image in Fig. 5 shows that, when a number was pressed, that number was displayed above pressed number. All these images show the case when '5' is touched.

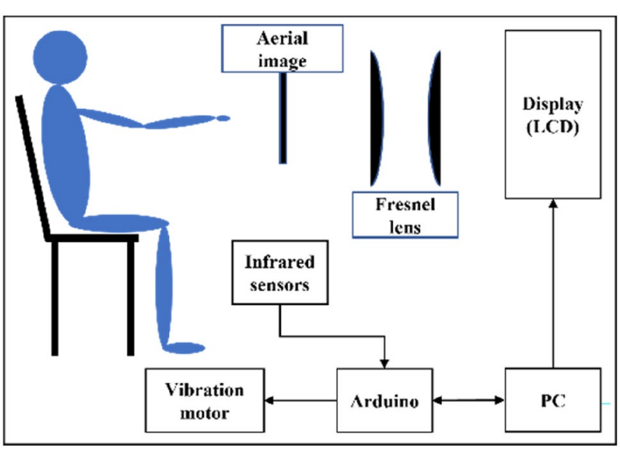


Fig. 1 Experimental apparatus

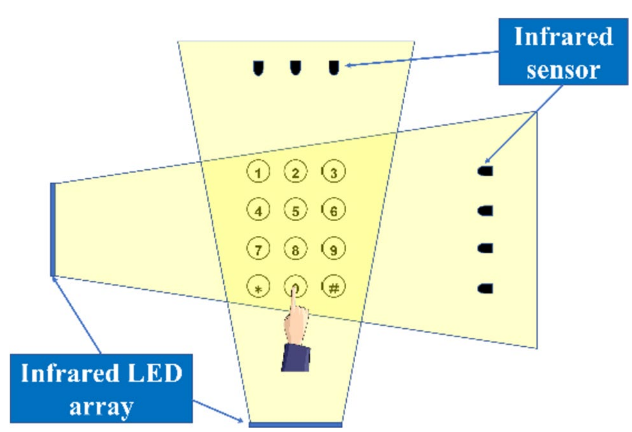
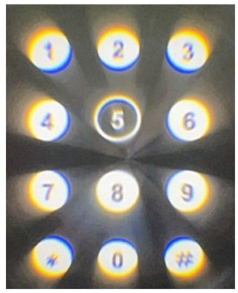
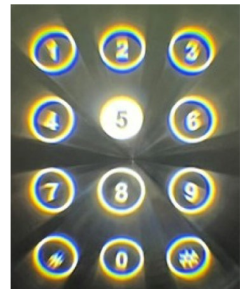


Fig. 3 Method to detect finger position using infrared sensors

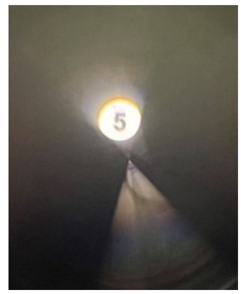
Fig. 4 Visual feedback by changing image (three types)



(a) Color inversion of the pressed number



(b) Color inversion of non-pressed number



(c) Delete non-pressed numbers

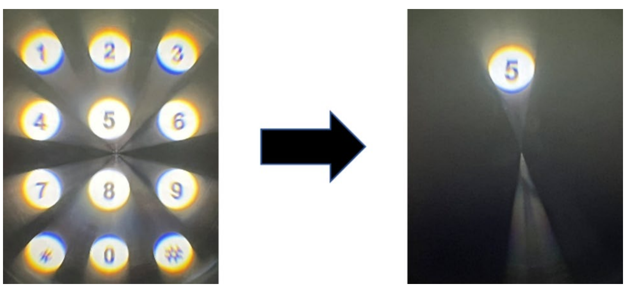


Fig. 5 Pressed number displayed above pressed number

Fig. 6 Vibration motor used in the preliminary experiment

2.4 Tactile feedback (preliminary experiment and Experiments 2 and 3)

As a preliminary experiment, we evaluated the improvement of usability of aerial display using vibration via a vibration motor to the sole of the foot. The purpose of this experiment is to confirm whether vibration to the sole of the foot is effective in operating the aerial display. Figure 6 shows the vibration motor used in this preliminary experiment (Motor size: 58*43*30 (mm), Rated voltage: DC 5 V, Rotation speed (no load): 4500 rpm).

We prepared five patterns of vibration duration to the sole of the foot: 0 ms (no vibration); 200 ms; 300 ms; 500 ms; and 1000 ms. All subjects wore the same slippers and operated the aerial display while stepping on the vibration motor. As an indicator of usability, we measured the time required for the subjects to touch their cell phone number three times in succession on the aerial display. To evaluate, we compared the time required for operation for each vibration duration and administered a questionnaire after the experiment. In the questionnaire, we asked, "Which is easier to operate, with or without vibration to the sole of the foot?" Three subjects participated in this experiment.

Figure 7 shows the time required for operation on each vibration duration. Although the required time with some vibration durations was shorter compared to touch in the case of 0 ms, no improvement was observed in the time required for operation by presentation of vibration to the sole of the foot. However, in the questionnaires, all subjects answered that "with vibration" was easier to operate.

Although we found no effect of presence or absence of vibration and vibration duration on the required time for

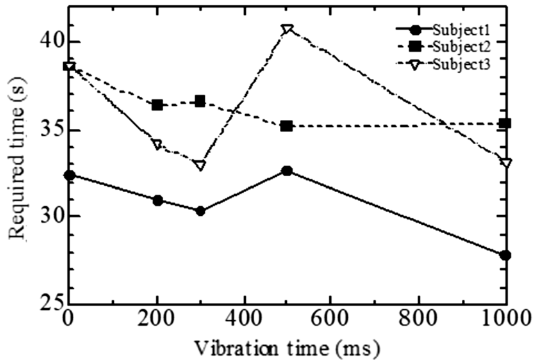


Fig. 7 Required time for operation for each vibration duration

Fig. 8 Vibration motor used in Experiments 2 and 3

operation, the questionnaire results indicate that this tactile feedback may contribute to the ease of operation of the aerial display. In other words, even if tactile feedback is not given to the fingertips directly, vibration to the sole of the foot could be effective in improving the usability of aerial display. Based on this result, we used vibration to the sole of the foot as tactile feedback in this study.

In Experiments 2 and 3, only tactile feedback was provided. All subjects wore the same slippers and operated the aerial display while stepping on the vibration motor. The vibration motor vibrated simultaneously as the subject touched the aerial image. Figure 8 shows the vibration motor used in this experiment (Motor size: 67*56*28 (mm), Rated voltage: 12 V-2200 rpm). This vibration motor is a DC motor that can be applied up to 12 V. The intensity of the vibration increased as the applied voltage was increased.

In Experiment 2, we changed the intensity of the vibration to the sole of the foot. We compared four patterns of applied voltage: 6 V (faint); 7 V; 8 V; and 9 V (fairly strong). In Experiment 2, the vibration duration was fixed at 300 ms.

In Experiment 3, we changed the vibration duration of the motor. We compared four patterns of vibration duration: 200 ms; 300 ms; 500 ms; and 800 ms. In Experiment 3, the voltage applied to the vibration motor was fixed at 8 V.

2.5 Auditory feedback (Experiment 4)

In Experiment 4, we provided only auditory feedback by playing a touch tone. We provided the touch tone simultaneously as the subject touched the aerial image. We compared four patterns of duration of the touch tone: 120 ms; 220 ms; 330 ms; and 650 ms.

2.6 Experimental items and procedure

We conducted the same procedure used in Scheffé's method of paired comparisons in all these experiments. In the paired comparison, two samples taken from several samples are compared. The preference of all sample combinations is evaluated and ranked. Table 1 summarizes the parameters prepared for each feedback. The subjects performed the same operation in the first and second conditions and evaluated the ease of operation in the second condition against operation in the first condition. Visual feedback has twenty combinations and others have twelve combinations. Ease of use was rated on a seven-point scale as follows:

3: Extremely good; 2: Good; 1: Somewhat good; 0: The same; -1: Somewhat bad; -2: Bad; and -3: Extremely bad.

The subjects entered their cell phone number once for each operation. Eight subjects participated in these experiments.

Statistical processing used the method advocated by Scheffe [16]. For each condition of each sensory feedback, we calculated the scale value by analysis of variance

Table 1 Parameters to be compared for each feedback

Sensory feedback	Types of feedback				
Changing image	Reverse pressed number	Reverse non-pressed number	Delete non-pressed number	Pressed number is displayed above pressed number	No image change
Tactile (intensity)	6 V	7 V	8 V	9 V	
Tactile (duration)	200 ms	300 ms	500 ms	800 ms	
Touch tone duration	120 ms	220 ms	330 ms	650 ms	

using Scheffé's method of paired comparison to test the main effect of each feedback and the significant difference between each condition. The lower the scale value, the easier it is to operate.

3 Results of evaluation of appropriate feedback parameters in visual, auditory, and tactile senses

3.1 Visual feedback by switching image (Experiment 1)

Figure 9 shows the scale values when switching the image in Experiment 1. The analysis of variance revealed a significant main effect: $F(4, 140) = 239.103$, $p < 0.01$. Color inversion of the pressed number was the easiest to operate and no image change was the most difficult. In other words, inverting the color of the pressed number is appropriate visual feedback in this experiment. The difference between inverting the color of the non-pressed number and deleting the non-pressed numbers was not statistically significant, but a significant difference was revealed between all other conditions ($p < 0.01$).

3.2 Tactile feedback by changing the intensity of vibration (Experiment 2)

Figure 10 shows the scale values when changing the intensity of the vibration in Experiment 2. The analysis of variance revealed a significant main effect: $F(3, 84) = 32.416$, $p < 0.01$. A 9-V voltage is the easiest and 6 V is the hardest to operate, and it is easier to operate with stronger vibration. In other words, 9 V is appropriate with the vibration motor in this study. The difference between 8 and 9 V was not statistically significant, but a significant difference is revealed between all other conditions ($p < 0.01$).

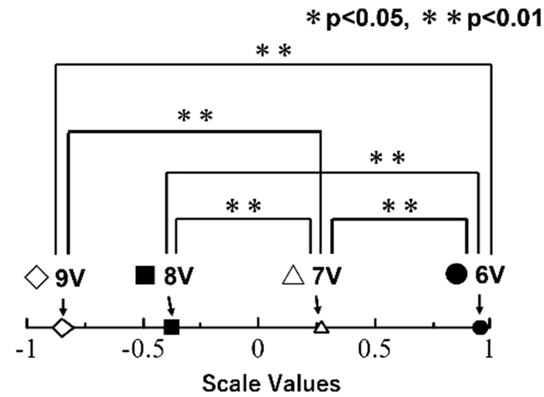


Fig. 10 Scale values in intensity of vibration (tactile feedback) in Experiment 2

3.3 Tactile feedback by changing vibration duration (Experiment 3)

Figure 11 shows the scale values when changing vibration duration in Experiment 3. The analysis of variance revealed a significant main effect, $F(3, 84) = 121.007$, $p < 0.01$. Vibration durations of 200 ms and 300 ms are the easiest and 800 ms is the most difficult to operate; somewhat shorter vibration durations make operation easier. Therefore, 200 ms or 300 ms are appropriate vibration durations in this study. The difference between 200 and 300 ms was not statistically significant, but a significant difference is revealed between all other conditions ($p < 0.01$).

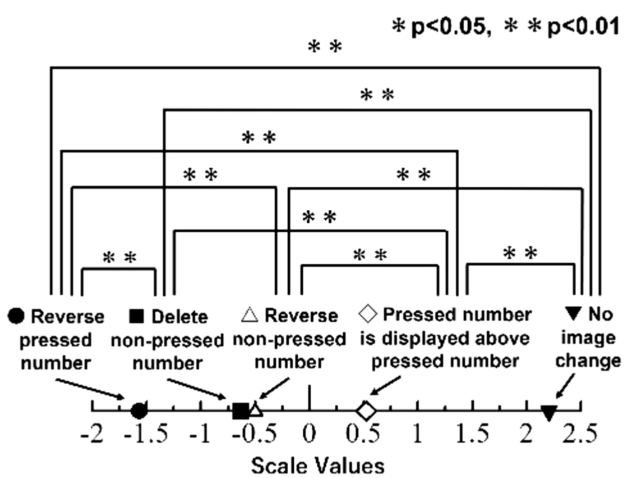


Fig. 9 Scale values in switching image (visual feedback) in Experiment 1

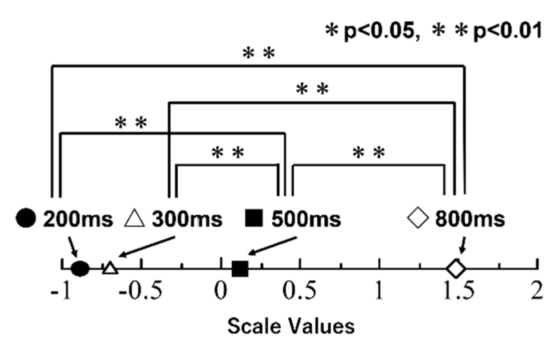


Fig. 11 Scale values in vibration duration (tactile feedback) in Experiment 3

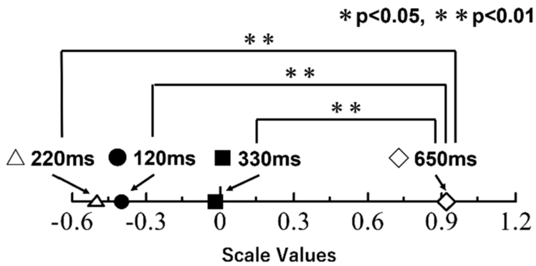


Fig. 12 Scale values in duration of touch tone (auditory feedback) in Experiment 4

3.4 Auditory feedback by changing duration of touch tone (Experiment 4)

Figure 12 shows the scale values when changing the duration of the touch tone in Experiment 4. The analysis of variance revealed a significant main effect: $F(3, 84) = 20.579$, $p < 0.01$. Touch tone at 220 ms and 120 ms is easiest and 650 ms is the most difficult to operate; thus, a shorter touch tone is easier. Therefore, 220 ms or 120 ms are appropriate durations of auditory feedback in this study. Multiple comparisons revealed significant differences between 120 and 650 ms, between 220 and 650 ms, and between 330 and 650 ms ($p < 0.01$).

4 Effect of feedback combination

4.1 Experimental detail

We conducted an experiment to determine whether there is an improvement in aerial display usability using multimodal feedback.

We provided unimodal feedback or multimodal feedback simultaneously as the subject touched the aerial image. Here, 'V' indicates visual, 'A' indicates auditory, and 'T' indicates tactile. We compared seven patterns of feedback: only visual (V); only auditory (A); only tactile (T); visual + auditory (VA); auditory + tactile (AT); visual + tactile (VT); and visual + auditory + tactile (VAT). Within the optimal feedback evaluated in the previous experiments, we used a 200-ms vibration duration of tactile feedback and a 220-ms touch tone duration of auditory feedback. Table 2 summarizes the seven types of feedback combined optimal feedback. The experimental procedure and evaluation method were the same as in our previous experiments. Eight subjects participated in this experiment.

Table 2 Seven types of feedback combined optimal parameters

Types of feedback	Optimal parameters		
V	Reverse pressed number		
A		220 ms	
T			9 V and 200 ms
VA	Reverse pressed number	220 ms	
AT		220 ms	9 V and 200 ms
VT	Reverse pressed number		9 V and 200 ms
VAT	Reverse pressed number	220 ms	9 V and 200 ms

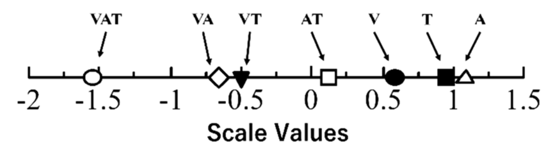


Fig. 13 Scale values of each feedback

	V	A	T	V+A	A+T	V+T	V+A+T
V		**	*	**	**	**	**
A			–	**	**	**	**
T				**	**	**	**
V+A					**	–	**
A+T						**	**
V+T							**
V+A+T							

Fig. 14 Significant difference of each feedback (*: $p < 0.05$, **: $p < 0.01$, -: Not significant)

4.2 Results of experiment

Figure 13 shows the scale values of the seven feedback types and Fig. 14 shows the significant differences between each condition. Since the analysis of variance revealed a significant main effect: $F(6, 294) = 143.687$, $p < 0.01$, combining each feedback is effective for usability of an aerial display. From Fig. 13, the multimodal feedback-combined three feedback (VAT) with the lowest scale value is the easiest to operate and the scale values of three types of feedback-combined two feedback are lower in the following order: visual + auditory (VA); visual + tactile (VT); and auditory + tactile (AT). A significant difference is revealed between V and T ($p < 0.05$). The difference between VT and VA, and between A and T were not statistically significant, but significant differences were revealed between all other conditions ($p < 0.01$).

Accordingly, we obtained usability of aerial display improvement without interference with each feedback when combining feedback. The combination of feedback is easier to operate than only one feedback and the combination of three feedback types is easier to operate than a combination of two, so combining three feedback types is optimal for the parameters used in this experiment. In other words, multimodal feedback is effective for aerial display operation.

5 Conclusion

We evaluated the ease of operation of aerial displays for various types of feedback through visual, tactile, and auditory senses and revealed the most effective feedback for each as follows: inverting the color of a pressed number in visual; a voltage of 9 V and vibration duration of 200 ms or 300 ms in tactile; and a touch tone of 120 ms or 220 ms duration in auditory. In visual feedback, if nothing changes, it is not clear whether the number is pressed or not. Inverting the color of the pressed number is the easiest for operating an aerial display because it is a change that is used in ATMs, smartphones, etc., and has become something we experience in our daily lives. In tactile feedback, a higher applied voltage and stronger vibration contribute to easier operation because a stronger stimulus can more easily provide the sensation of pressing the numbers. The longer the vibration duration, the more difficult to operate. Too long a vibration, such as 800 ms, is annoying because the touching operation to press from one number to the next does not need to exceed 800 ms. As with the vibration duration, for auditory feedback, a touch tone of 650 ms seemed annoying because it is too long. We found that it is necessary to provide optimal visual, auditory, and tactile feedback for touching an aerial image that does not have touch sensation. Vibration to the sole of the foot using vibration motor is easy and inexpensive implementation of the equipment and is suitable for operating aerial displays in a standing position outdoors. However, a disadvantage is that users are not used to recognizing aerial display operation through vibration to the sole of the foot when they touch the aerial image for the first time.

In addition, we revealed that providing multimodal feedback that combines these optimal feedback types is more effective for improving the usability of aerial display than unimodal feedback. As shown in this experiment, aerial display is easy to operate by combining feedback methods, each of which is optimized as unimodal feedback. Furthermore, we revealed that, if we use the optimal feedback methods, the combination of two modalities rather than only a single modality and the combination of three modalities rather than the combination of two modalities makes the aerial display easy to operate.

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