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Vibrotactile Displaying of Flight Attitude with Combination of Multiple Coding Parameters

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Abstract: Vibrotactile displays have been reported effective in enhancing awareness of flight attitude for pilots and releasing other heavily loaded sensory channels. Although some work have been done on vibrotactile coding of flight altitude, there is lack of a systematic investigation into coding methods with combination of multiple coding parameters. In this paper, seven coding methods with combinations of multiple coding parameters (location, rhythm, intensity, and mode) were systematically studied to cue flight attitude for pilots with a vibrotactile vest. We conducted two psychophysical experiments in a static tactile sensory environment in which the attitude commands in the form of vibrotactile feedback are presented randomly, and quantitatively evaluated the effectiveness of the vest according to the users' recognition accuracy, reaction time and information transfer rate. The results show that vibrotactile vest is effective to cue attitude information. The preferred coding method with combinations of location, rhythm and mode allowed users to perform with lowest reaction time and highest recognition accuracy and yield about 255 bits/min of information transfer rate. Overall**,** the presented work provides valuable insights and guidance for the design of haptic displays for vibrotactile aids for the pilots.

Keywords: flight attitude; vibrotactile coding; vibrotactile display

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1. Introduction

Flying an aircraft especially the fighter plane is a challenging activity, and exposes the pilot to many potential hazards. One of the most significant of these is spatial disorientation (SD), which is a term used to describe a variety of incidents occurring in flight where the pilot fails to sense attitude, or motion of one's own aircraft relative to the earth or other significant objects [1]. In aviation accidents and incidents, SD accounts for some six percent to 32 percent of major accidents, and some 15 percent to 69 percent of fatal accidents [1].

There are several factors causing SD problem such as visual and vestibular illusions, fatigue driving, instrument fault, and environmental factors (flight in rain, above sea, through cloud) [1] [2] [3]. The decline in situation awareness of pilots due to these factors is the direct reason to cause SD problem [1]. Traditional aircraft instruments such as gyro-stabilized altitude indicator, HUD, SVS (synthetic visual system), EVS (enhanced visual system) et al, provide pilots the situation of aircraft via visual or audio channel [4]. However the traditional instruments will occupy additional audio-visual resources [5]. Pilots needs high concentration of the auditory and visual channel in accessing information from the vicinity for safe ambulation (e.g., approaching objects, acoustic and visual signals from instruments and alert), the two channels will not available for other cues. What's more, the pilot cannot keep the situation of aircraft well via the two traditional senses when flying aircraft above the sea [2], through rain and cloud [3], or in condition of altered gravitoinertial acceleration [6-8].

According to previous psychological studies, the issues above may be solved by using a free sensory channel liking tactile sense, for example, the multiple resource model of human information processing predicts no performance degradation when independent resources or information

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channels are used to present information (e.g. refer to [9]; [10]). The advantage of touch is that they do neither block the visual nor the auditory sense [11]. Employing the tactile channel may release other heavily loaded sensory channels, therefore potentially providing a major safety enhancement [12]. Due to the convenience and real-timeliness for changing the pattern of tactile stimulation, vibratory stimuli have been widely adopted in haptic displays.

Recently, Favorable effects of vibrotactile displays on navigation performance, situational awareness, and workload reduction have been shown in many application such as vehicle driving, pedestrian navigation, particularly in the high workload group[13, 14][15][16][17][18]. To date, very few studies have examined the effective implementation of vibrotactile displays for conveying flight attitude information of aircraft. The flight attitude is an important parameter for pilots to maintain their awareness of situation of aircraft [3, 19]. During the flight, the pilots should ascertain within about 5° of pitch and roll information of aircraft. It is required that the vibrotactile display provide multiple tactile patterns to the pilots [3]. The TSAS (tactile situation awareness system consisting of 8*5 matrices of pneumatic tactors, developed by Rupert and colleagues) is perhaps the most fully implemented and tested system. The resolution of encoding angles is high to about 5° in fine flight [3]. In their coding methods, vibrotactile patterns with different vibration intensity were employed to cue precise directional information. However, coding methods with intensity did not produce intuitive vibrotactile patterns mapping corresponding angles, and need long time of training to master the vibrotactile commands conveyed by the TSAS in practice.

The coding strategies for these haptic displays have so far been rather basic [20]. An intuitive and well-perceivable coding method can reduce training time and increase user acceptance of tactile device. According to previous work of enhancing pilots' spatial awareness with vibrotactile devices, the parameters that can be used to encode flight information include 3 basic dimensions: spatial location, temporal rhythm and intensity of vibration [21]. However the systematic investigations into coding strategies for conveying flight attitude information with combination of multiple coding parameters are exceptional rare in most of reported works. Combination of multiple coding parameters are essential to improve the effectiveness of vibrotactile display, since we can determine the vibrotactile coding capacity of each vibration parameters and differences between the perceptions of vibrations with different parameters. The test results of vibrotactile display designed by [22, 23], illustrated that the best way to encode information with tactile channel is using the coding parameter as many dimensions as possible. For instance, spatiotemporal patterns will yield superior identification over spatial patterns and patterns encoded by a single motor's intensity for an area of skin [24].

The goal of this work is to investigate preferred coding methods with combination of multiple coding parameters for cueing precise directional information through vibrotactile feedback, using well perceivable and easily comprehensible vibrotactile patterns. The torso provides an extensive haptic space for presenting tactile information, with approximately half the total surface area of the body. The skin covering the torso is capable of precisely encoding information since it contains hundreds of mechanoreceptors [25, 26]. In addition, a belt-type device can be worn under a coat without attract public attention. Therefore, we focus on vest-type device to convey vibrotactile feedback for flight attitude of aircraft, and systematically investigated the coding methods with combination of parameters: location, rhythm, intensity, and modal.

2. Materials and Methods

2.1 Vibrotactile actuators

There are three types of actuator available for haptic display: electromagnetic (DC coin motor or linear motor), pneumatic, direct electric tactor in TSAS. The direct electric tactor can evoke a strong tactile sensation, however the range between absolute threshold and pain is very small; the amplitude of pneumatic tactor is fix [21]. We selected DC coin motor over the other types due to its lightweight, small size, low price and easiness of adjusting the amplitude. In order to increase the perceived intensity in flight condition, 2 motors were overlapped as a vibrotactile unit. We used 20 KOTL

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C1234B016F coin vibration motors operating at 3V of voltage and about 140 Hz of frequency (http://www.kotl.cn/cn/default.aspx). The intensity of vibration was controlled by PWM duty. Objective and basic psychophysical tests have been conducted for actuators in our previous work [27]. For the convenience of narration, we used the phrase "tactor" to represent the vibrotactile unit used in this study.

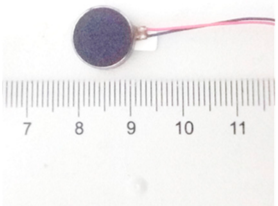

Figure 1. Vibrotactile actuator

2.2 Design of wearing vest

The vibrotactile display was designed by taking the inspiration from TASA proposed by Rupert [3], which consists of 8 column of 5-tactor array. Since there is significant discrimination between the perceptions of vibrotactile stimuli from the cardinal sides of torso [18, 28, 29], 4 columns of tactors were set on the vest. Each column consists of 5 tactors. To make the vibrotactile vest to suit for everyone, we selected the high elastic material as the cloth of vest. In order to facilitate user's localizing the vibrations from different tactors, the tactors should be arranged properly to make distance of each adjacent pair as far as possible. After wearing the vest, the tactor approximate distribution of tactors around the torso is depicted in Figure 2.

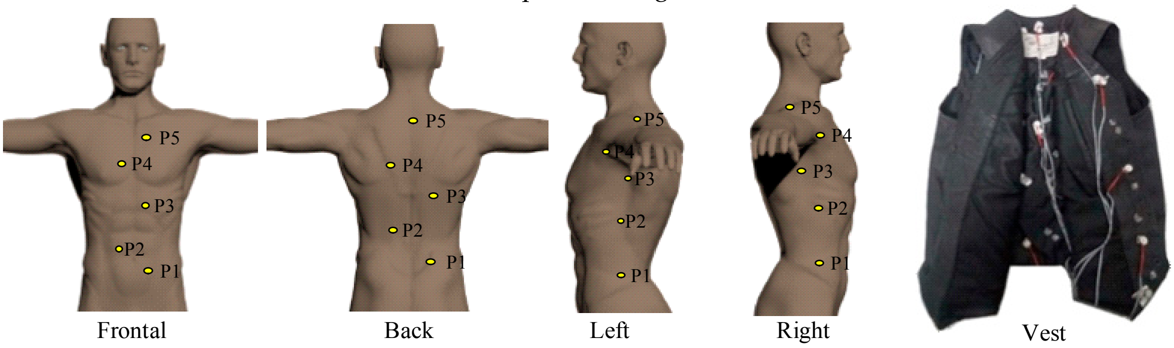

Figure 2. The arrangement of distribution of tactors around the torso and prototype of vibrotactile vest. In frontal of body, 5 tactors locate on lower abdomen, upper abdomen, slightly below the chest, middle of chest and below of the clavicle respectively. In back of body, 5 tactors locate on the hip above, Central spine, right shoulder, left shoulder, and cervical spine respectively. In the left or right side of body, 5 tactors from down to up locate on hipbone above, rib, oxter, chest and shoulder respectively.

2.3 Tactile Coding Parmeters

A fundamental factor that may affect effectiveness of vibrotactile devices is how this altitude information is encoded [3]. In the following section, several coding strategies with combination of multiple vibration permeters are developed to display the flight attitude in a vibrotactile vest.

Flight attitude of an aircraft can be divided into four basic states: pitch down, pitch up, roll left and roll right. The angle in each state range from 0° to 90°. The definition of angle of flight attitude, the method of vibrotactile displaying of different flight states, and schematic diagram of vibrotactile system were illustrated in Figure 3c.

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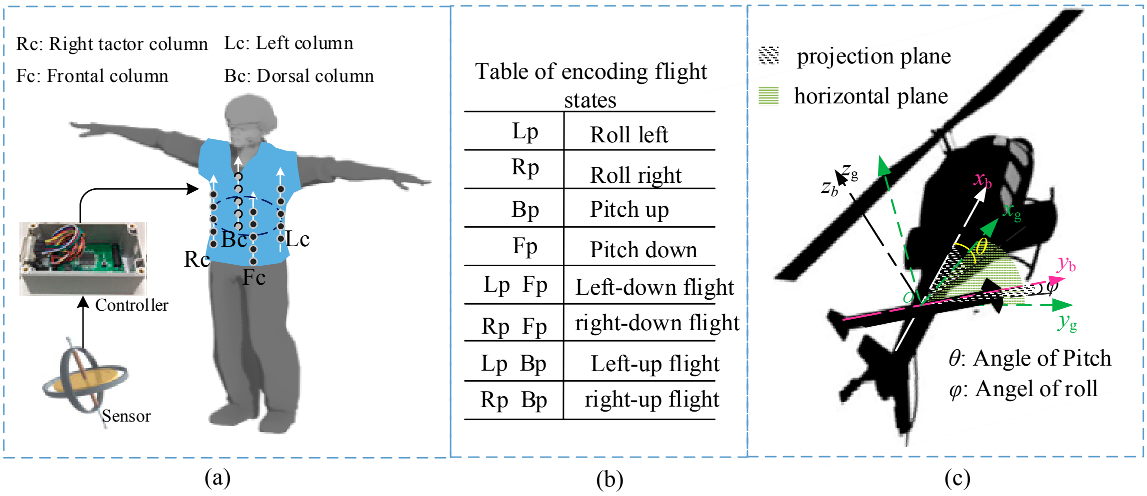

Figure 3. Overview of vibrotactile system for cueing flight attitude. (a) System block diagram of vibrotactile TSAS and Tactor arrangement around the torso of pilot. The controller receive flight attitude information from the geomagnetic sensor and activate vibrotactile vest to vibrate in the pattern corresponding to the attitude. (b) Definition of Flight attitude information of aircraft, (b) schematic diagram encoding different states of flight attitude.

As seen in Figure 3b, the angle of pitch (θ) and roll (ϕ) were be defined as an included angle between the earth-surface inertial reference frame ($O\ x_g\ y_g\ z_g$) and Aircraft-body coordinate frame ($O\ x_b\ y_b\ z_b$). The state information of aircraft were be rendered by the vibration on corresponding column or combination of four columns of tactors. In order to embody the S-R compatibility of space [30], the frontal, back, left and right column of tactors were employed to cue angles in pitch up, pitch down, roll left and roll right state respectively as illustrated in following figure. When both pitch and roll angles need to be rendered, the corresponding columns of tactors will simultaneously be activated to vibrate. As illustrated in Table 1, Angle in each flight state were divided into 4 flight status: Normal flight ranged in [5° 50°) with 5° apart, Acrobatic flight ranged in [50° 90°) with 10° apart, Fine flight ranged in [0° 5°), and Emergency ≥90°.

Table 1. Division of angle range in each flight state

Group	Ranges of angle	Flight status
	≥90°	Emergency
5	[70°,80°)[80°,90°)	Acrobatic flight
4	[50°,60°)[60°,70°)	
3	[35°,40°)[40°,45°)[45°,50°)	Normal flight
2	[20°,25°)[25°,30°)[30°,35°)	
1	[05°,10°)[10°,15°)[15°,20°)	
	[0°,5°)	Steady flight

In order to distinguish the steady flight from the fault of vibrotactile system, attitude of fine flight was encoded by the vibration from the tactor placed at the bottom of the corresponding column. Since the aircraft is in steady flight status in most of time, this tactor was controlled to vibrate with weak intensity and short duration considering energy efficiency. Angle of more than 90° was cued by simultaneous vibration of all tactors in corresponding column. Thus the range of angle need to encode in each flight state is [5°, 90°) with 14 angle intervals.

The parameters that can be used to encode angle and flight state include spatial location, intensity, rhythm and mode of vibration, which can be classified into two categories considering the number of vibrating tactors as illustrated in Table2.

Spatial characteristics of a vibrotactile sensation is determined by the location of vibration stimulus on a vibrotactile display [31]. Of the four coding parameters shown in Table 2, the parameter of location is therefore mandatory to encode attitude information. But the only using parameter of location is not enough to encode 56 (14*4) angle intervals with only 20 tactors. Thus other parameters in Table 2 should selected to combine with location for cueing all the angle intervals.

There are about 3 identifiable levels for intensity of vibration on torso according to the results from our previous psychophysical test for actuators [32]. Thus the identifiable levels of intensity can be used to render angle information more precisely. For instance, if a tactor is employed to cue angle from 0° to 20°, the weak, middle and strong intensity of vibration can be employed to indicate [5°, 10°), [10°, 15°), [15°, 20°) respectively. However the coding capacity of cuing information with intensity is limited, since there are only 3 tactor amplitude intensities can be easily identified [33].

The rhythm of vibration is a time-domain parameter which can also be used to improve precision of cueing angle. As is similar with the parameter of intensity, 1 time, 2 and 3 times of vibration can be employed to cue [5°, 10°), [10°, 15°), [15°, 20°) respectively. What's more, duration length of vibration is also a useful parameter to encode information, which will be illustrated briefly in next section.

Table 2. Coding parameters for tactors

Parameters for single tactor	Vibrating location (P), Intensity (I), Rhythm (R)
Parameters for multiple tactors	Vibrating mode (M)

Activating multiple tactors in vibration modes is another useful coding method. The two main parameters that control the feeling of different vibration modes are the *duration of stimulus* (DoS) and the *stimulus onset asynchrony* (SOA) [34]. By adjusting the parameter of DoS and ISI, we can make multiple tactors to be perceived as different vibrating modes as illustrated in **Figure** 4. The continuous vibration is also called tactile funneling illusion. When two tactors vibrate simultaneously on skin, the perceived vibration of a virtual tactor located between the tactors will be felt [35, 36]. The continuous vibration called "vibrotactile apparent movement." When activating two or more tactors sequentially with a certain timing, the stimulation point is perceived as if it is moving continuously from one location to another, although the real stimulating points are discrete [35, 36]. Discrete motion will be perceived when the adjacent tactors are activated sequentially with an inter-stimulus interval (ISI).

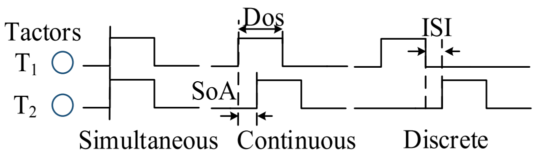

Figure 4. Schematic diagram of tactile apparent motion; *duration of stimulus* (DoS), the *stimulus onset asynchrony* (SOA), *Inter-stimulus interval* (ISI).

From what described above, the flight attitude can be displayed using coding methods with combination of two parameters or three parameters in Table 2. Therefore two psychophysical experiments were designed to investigate the preferred combination of two and three parameters respectively.

3 Psychophysical Experiments

The tactile experiments are static stimulating tests, where the subjects wearing the vibrotactile vest perceived vibrations encoding attitude information in a stationary condition. The objective of this experiment is to investigate preferred coding method with combination of multiple vibration parameters.

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3.1 Participants

20 subjects participated in this experiment. Their ages ranged from 20 to 30, all of whom were right-handed and reported to have no known cutaneous or kinesthetic problems.

3.2 Experimental Design

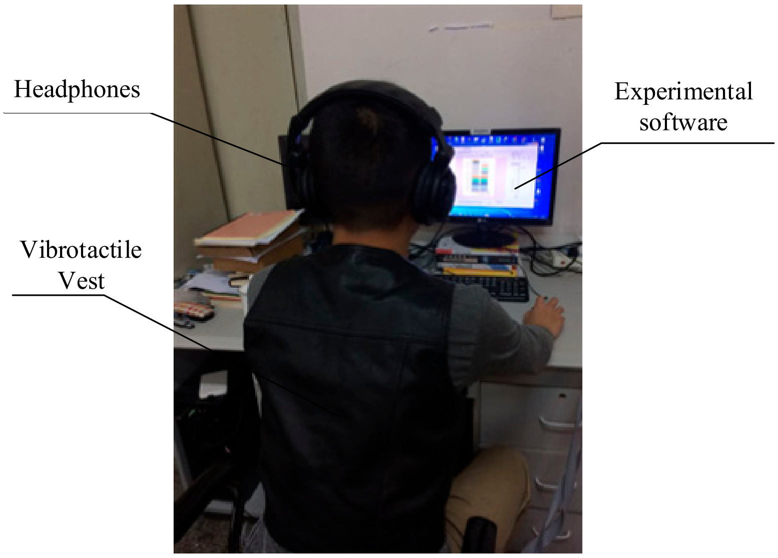

Figure 5. A subject during the experiment

Independent variables: We employed a within-subjects repeated measures design, with coding methods (CM) as a between-subject factor (Figure 6 and Figure 8, LR, LM, LRI1, LRI2, LRI3, LRM) and flight states as a within-subject factor (roll left, roll down pitch up, pitch down).

Dependent variables: Recognition accuracy (RA), reaction time (RT) were implemented to evaluate the effectiveness of tactile belt for cueing angle information.

Recognition accuracy (%) defined as the percentage of correct recognition of tactile commands. Under the condition of correct judgment for flight states, we classified an identification with difference between a reported and set angle not more than 5 degrees as a correct recognition, otherwise as a wrong recognition. The Recognition accuracy is proportion of number of correct recognitions to total number of commands.

Reaction time (s) defined as elapsed time between finishing the display of the vibrotactile command and the moment when subject has reported a given angle. It should be noted that the time spent on clicking some buttons for reporting the corresponding angles were not included in the reaction time. (The time taken for clicking buttons can be recorded in experimental software).

Information transfer rate (bits/min): To statistically analyze the preference of coding methods, we further calculate the information transfer rate (ITR) as illustrated in fig. The most popular method for ITR calculation in brain–computer interface (BCI) research was defined by Wolpaw et al in 1998, which is a simplified computational model based on Shannon channel theory under several assumptions [37, 38].

$$B_t = \frac{60}{T}\left(\log_2 N + P \cdot \log_2 P + \log_2 \left[\frac{1-P}{N-1}\right]^{(1-P)}\right) \quad (2\text{-}6)$$

Generally, B_t in bits/min is used to indicate the ITR, N is the number of possible choices and P is the probability that the desired choice will be selected, also called target identification accuracy or classifier accuracy. T (seconds/symbol) is the time needed to convey each symbol. In our current study, N is the total number of angles (60), T can be seen as the reaction time for each angle, and P is obviously the recognition accuracy. The ITR is more comprehensive than recognition accuracy or reaction time for taking account of both the two evaluating criterion.

3.3 General Procedures

At the beginning of the experiment, subjects were prompted to sit comfortably on a chair. At the beginning of experiments, subjects were prompted to sit comfortably on a chair. They were asked to wear headphones playing white noise (see Figure. 6). The headphone was important to block out sounds from the vibrotactile display as well as the office environment. Before the experiment started, the objective and the function of the vest was explained. 52 vibrotactile patterns encoding attitude angles except the angle of 0~5° and more than 90° were presented in sequential order to familiarize the subjects with the meanings of vibrotactile stimuli. For each coding method, the subjects should receive training for 10 minutes before starting formal experiments.

In the **formal experiment**, 52*3 trials were presented for each condition via an experimental software. Thus, for each subject and coding method, a total number of 2,548 (52*3*7) trials were recorded throughout the whole experiment. At end of each trial, Subjects need to report the flight attitude angles by clicking corresponding radio button in the experimental software. To avoid fatigue, participants could take a break between trials and sessions on request. In order to avoid biased responses, angles were presented in a pseudo-randomized order. The subjects needed to select the direction within the prescribed time (6s). To reduce the practice and habituation error easily occurring in a psychological experiment [35], a random vibration pattern different from before was given to the subject when a judgment timed-out occur. During the **formal experiment** no feedback about correctness of the answers was given during the experimental session. The subject's selected angle and reaction time were recorded in a database. After completion of each of the seven conditions, subjects were asked to complete a questionnaire and provide a ranking of their preferred vibrotactile coding method.

To assess the impact of each condition on the performance, we analyzed the data by employing a one-way within-subjects design ANOVA, using standard software (IBM SPSSS statistics 20, IBM Corp., USA). The within-subjects factor is the direction of the coding methods. Simple main effects comparisons and post hoc analysis with Bonferroni correction were further performed to test for significant interaction effects. Wilcoxon signed rank tests and Friedman tests were conducted to compare the preferences among coding methods. We employed a one-way repeated measure Multivariate analysis of variance (MANOVA) to test our objective measures.

3.4 Experiment 1

The Experiment 1 was conducted to find the prefered Coding methods with combination of two parameters

3.4.1 Vibrotactile Coding design

Since the parameter of vibrating location is mandatory in cueing information, there were three different combinations with two parameters as illustrated in **Figure 1**.

LI coding method. The angles within group shown in Table1 was rendered by vibrotactile pattern with different intensity as illustrated in Figure **4**a). The LI The most obvious merit of this coding method is that the cueing time is short with SOA set to 300ms.

LR coding method. The main idea of the second rendering method is to activate different times of corresponding tactor, depending on the angles within group, as depicted in Figure 3b). The ISI and DoS was set to 60 ms and 150ms respectively for each tactor at all angle levels.

LM coding method. For the third rendering method, we designed a pattern eliciting the coding parameter of mode as described in section 2.2. The angles within group were encoded by activate adjacent pair of tactors in different vibrating mode (simultaneous, continuous and discrete method). As is similar with coding method LR, the same intensity was applied to all angle levels.

Overall the intensity, rhythm and mode is combined with lactation in LI, LR, *and* LM coding method respectively to cue all the angles in each flight state.

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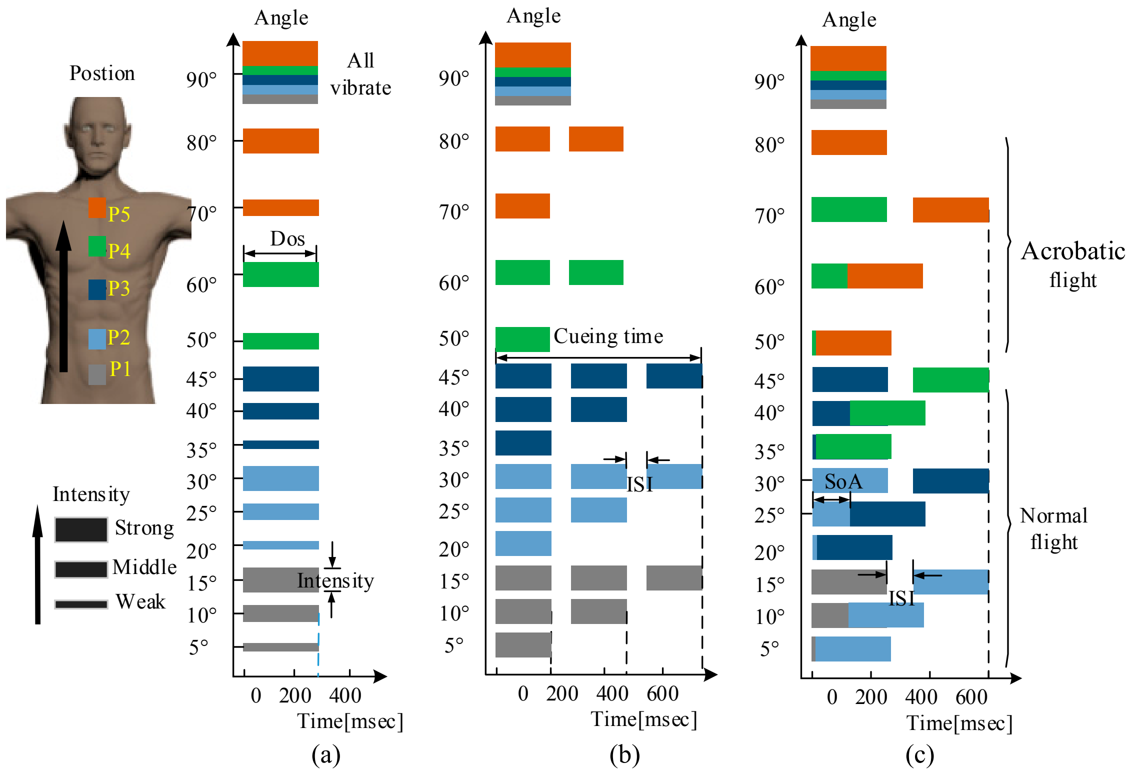

Figure 6. Schematic diagram of coding methods with combination of two parameters. a) coding with combination of location and intensity (LI), b) location and rhythm (LR), c) location and intensity (LM), for the convenience of labeling angel intervals, 5° in vertical coordinate indicates interval [5° 10°) in table3 , 10° indicates [10° 15°) and so forth. The cueing time is maximum time to convey a tactile pattern. Different color blocks represent different tactors in a tactor column. The normal flight angle (5~50)

3.4.2 Experimental Results

Fig. 7 depicts the mean recognition accuracy and reaction time in each rendering methods. The maximum recognition accuracy and reaction time from a total of 2,548*20 trials was about 61 percent (SD: 0.07 percent) and 0.75 s (SD: 0.04 s).

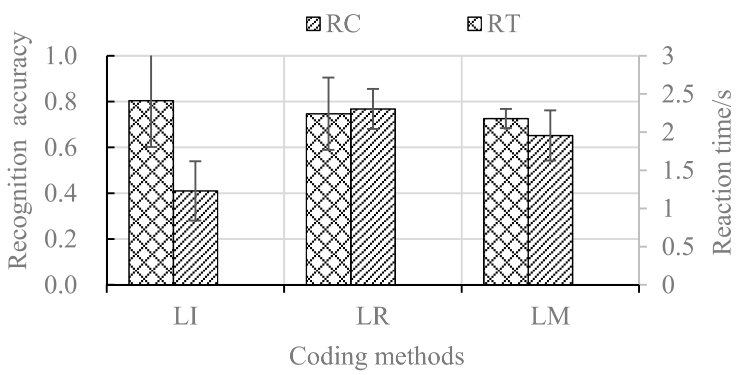

Figure 7. Recognition accuracy (%) and reaction time (s) for each coding method in experiment 1. Error bars indicate standard error.

To quantitatively analysis the preference of combinations in term of recognition accuracy, POST hoc tests with Bonferroni were performed.

Table 3. Post hoc Test for different combinations of coding parameters with LSD correction

CM (I)	CM(J)	Mean Difference /I-J (Z)	Sig
LI	LR	-.3580*	.000
LI	LM	-.2420*	.005
LR	LM	.1160	.122

*. The mean difference is significant at the .05 level

As seen in Table 3, both LM and LR perform better than LI with significant difference ((Z=-**0.3580**, p =.000), (Z=**0.160**, p =0.005) respectively). LR perform better than LR but without significant difference (Z=**0.032**, p =0.122). As seen from the figure 6, the cueing time of LR is shorter than that of LM. Overall, it can be obtained that the PR is the preferred combination of two vibration parameters.

3.5 Experiment 2

In the experiment 1, we have determined that the LR is the preferred coding method of cueing attitude. In order to study whether there is improvement on performance when adding another vibration parameter at the basis of LR coding method, another experiment was carried to determine the preferred combinations of three vibration parameters.

3.5.1 Vibrotactile Coding Design

To enhance the discrimination between groups in Table 1, the vibrating intensity or mode was employed as an additional coding parameter to facilitate memory and mastering of the coding methods, and improve recognition accuracy.

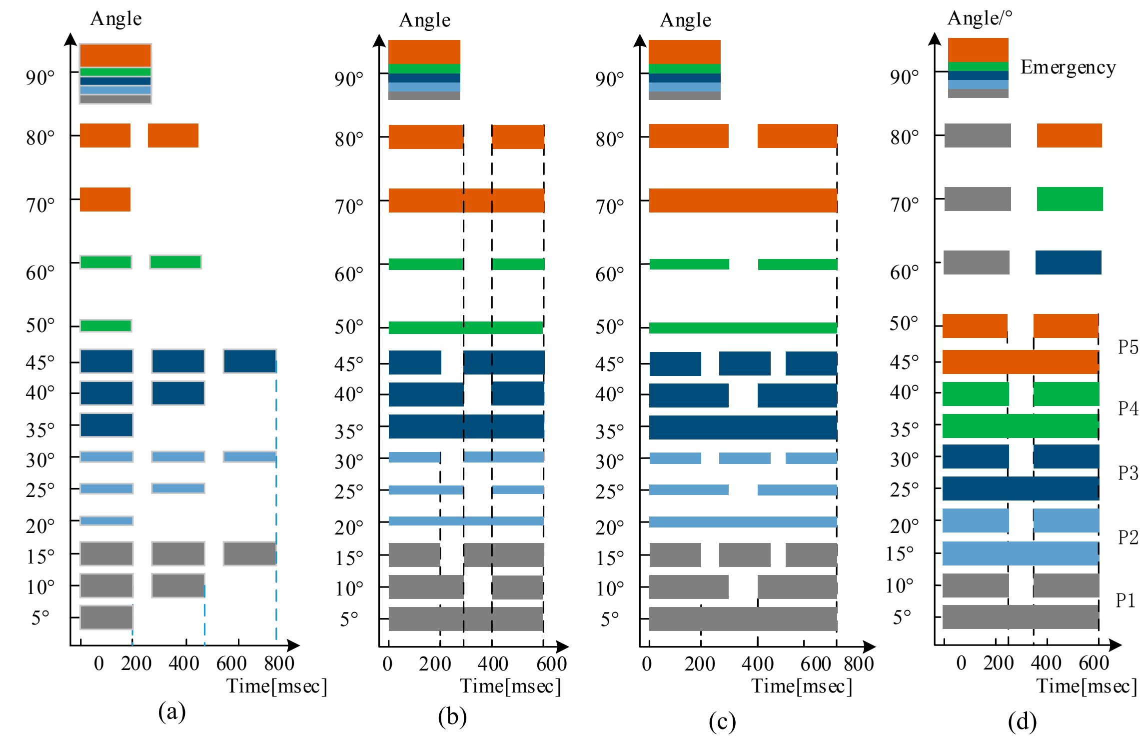

Figure 8. Schematic diagram of coding methods with combination of three parameters: a) location, rhythm and intensity（LRI1）b) location, rhythm and intensity （LRI2） c) location, rhythm and intensity（LRI3）d) location, rhythm and mode（LRM）.

LRI1 coding method combines with of the parameters of location, rhythm and intensity. Compared to the LR coding method, the LRI1 coding method takes vibrating intensity as the additional coding parameter to enhance the discrimination between groups. In accordance with LRI1, the, LRI2 also employed vibrating intensity as the additional coding parameter, but implemented the rhythm with different duration of stimulus as main coding parameter. As similar with LRI1, The LRI3

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make use of vibration times to indicate different angles within group, but the cueing time for all the angles are same. In order to facilitate memory of vibrotactile patterns mapping angles, in LRM method, vibrating mode was employed as an additional coding parameter to distinguish between normal and acrobatic flight as illustrated in Figure. 8 (d).

3.5.2 Experimental Results

The maximum recognition accuracy and reaction time from a total of 2,548*20 trials was about 95 percent (SD: 0.06 percent) and 0.53s (SD: 0.03 s). It can be seen that in all conditions, the coding method with combination of 3 parameters performed better than that of 2 parameters.

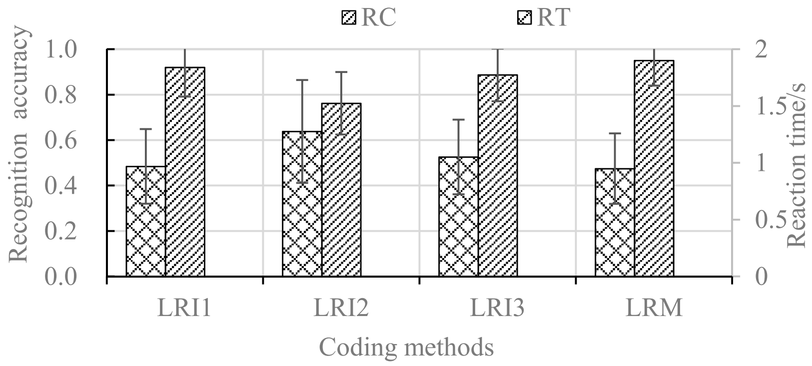

Figure 9. Recognition accuracy (%) and reaction time (s) for each coding method in experiment 2. Error bars indicate standard error.

To quantitatively analysis the preference of combinations in term of recognition accuracy, POST hoc tests with Bonferroni were performed.

Table 4. Post hoc Test for different combinations of coding parameters with LSD correction

CM (I)	CM(J)	Mean Difference /I-J（Z）	Sig
LR	LRI1	-.17367*	.004
LR	LRI2	-.00610	.916
LR	LRI3	-.11890*	.043
LRI1	LRI2	.17976*	.000
LRI1	LRI3	.05476	.219
LRI2	LRI3	-.12500*	.007
PRM	PRI1	0.01424	.694

*. The mean difference is significant at the .05 level

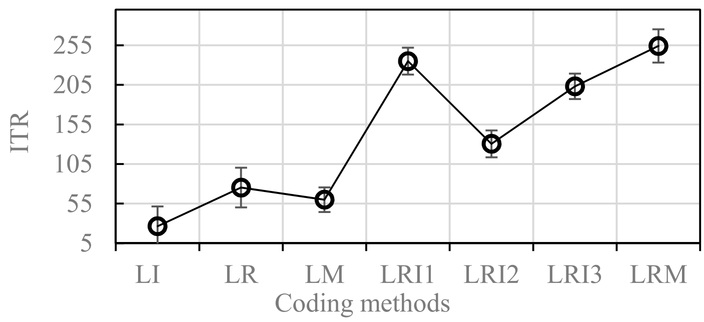

Figure 8. Information transfer rate for preference of combination CM and IBIPA on reaction time; the error bars indicate standard error.

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As seen above the **Table 4 and Figure 8,** there is significant effect of CM on ITR, and LRM has the highest ITR among the levels of CM, which in accordance with results of ANOVA analysis (**Table 4**).

In order to further improve the vibrotactile display. We carry a 3-way repeated measure MANOVA to study whether there is significant difference of performance between levels of each coding parameter in preferred coding method (LRM). There are 4 independent variables: flight states (4 levels), Locations (5 levels), Rhythms (2 levels), and 4 dependent variables: RAs.

Table 5. MANOVA in the optimal coding method

Source	Quadratic sum	Dof	mean square	F	Sig.
States	.019	3	.006	.197	.898
Locations	.281	3	.094	2.970	.032
Rhythms	.109	2	.054	1.721	.181
States * Locations	.323	9	.036	1.136	.337
States * Rhythms	.121	6	.020	.638	.700
Locations * Rhythms	.049	4	.012	.385	.819
States* Locations * Rhythms	.292	12	.024	.770	.681

As seen in above table. There are no significant difference of performance between levels the coding parameters, expect the parameter of location ($F_{(19,4)}$=2.97, p=0.032). In order to further improve the design of tactile device and its coding strategy. We analysis the correct percentage changing with set angle as shown in following figure.

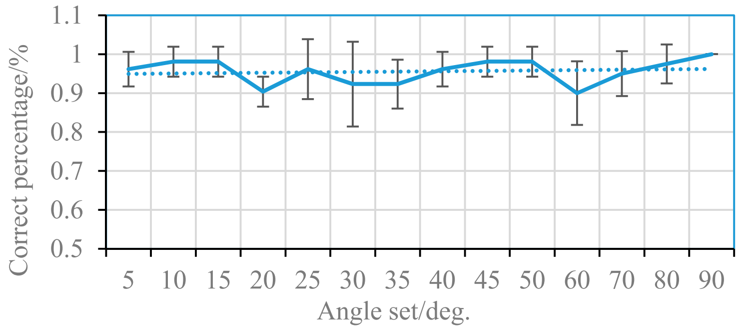

Figure. 9 The curve of recognition accuracy (RA) change with set angle in preferred coding method. Error bars indicate standard error.

As seen above figure, the average RAs of all the angles exceed 90%. The RAs at the angles ranging from 20° to 40° and 60° appears greater volatility than at other angles. These angles were cued by tactors P2, P3, and P4 respectively. It is in accordance with the result of table 6 and Questionnaire that most of subjects reported that they have difficult in discriminating vibrations from these tactors. It suggests that the setting sites for these tactors should be adjusted to further improve the perceptive performance of the vest.

4. Discussion

In this study, we have designed a vibrotactile vest to cue of attitude information of aircraft for pilots and systematically investigated the efficiency of vibrotactile coding methods with combination of multiple vibration parameters.

The experimental data shows that, in general, the participants were positive about the use of vibrotactile belt to provide directional guidance. The experimental results also indicate that the rhythm perform well than available other coding parameters (see Figure 3). It should be noted that differences between the vibrotactile patterns might have been stronger if participants were driving a

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real aircraft instead of being seated, due to the continuous change of direction in practice. Besides the design of the current vibrotactile vest is convenient to wear for people of different waist sizes.

4.1 Comparisons with previous work

As a review of previous TSASs successfully implemented in aviation, there are several types of vibrotactile displays to cue situation information for pilots [3, 19, 39]. The comparison between their and our work on tactor cued is illustrated in following table.

Table 6. Performance comparison between our work and previous TSASs

TSASs	Tactor arrangement	Performance	
		Number of Used tactors	Resolution
This work	4*5 matrix vest	20	5°
[3]	8*5 matrix vest	40	5°
[39]	8-tactor belt	8	Simple
[19]	60-tactor jacket	60	5°

The TSAS consisted of 40 tactors developed by US Navy were implemented to cue Flight attitude using 40 tactors [3]. The belt-type TSAS consisted of 8 tactors was used to indicate simple attitude information (pitch up, pitch down, roll left and roll down). The vibrotactile display in our work present attitude information of same resolution with TSAS proposed by Rupert and Eriksson but using less tactors.

Although some TSASs in reported work were also used to cue other situation information such as flight height, drifting direction, which we did not include in the current work, these information can be presented by improving the coding strategies in our current vibrotactile design. It will discussed in following section.

4.2 Limitations of our work

Although the TSAS in current work is successfully implemented to cue attitude situation information and yield resolution of 5°, but not indicate other situation information such as flight height, drifting direction and velocity, which is also important to enhance the situation awareness and reduce sensory workload during flight [21][40]. Fortunately, it can be achieved by improving the coding strategies to present integrated situation information without changing the hardware design of current vibrotactile system. For instance, the current vest consists of 5 rows of 4-tactor arrays, all the rows from down to up can just be used to display 5 levels of flight height (Low altitude flight, Hollow flight, High-altitude flight, ultrahigh altitude flight) respectively. The funnel tactile illusion can be implemented in each row to cue precise drifting direction and the horizontal velocity. However there are several problems in coding integrated situation information. For example, A critical challenge in integrated vibrotactile coding strategy of displaying situation information is how to avoid confuse means between vibration patterns encoding different types of information. Another challenge is to determine the optimal parameters of controlling the TSAS. An important parameter in the current integrated vibrotactile need to be determined is the interval between cueing attitude and drifting information.

5. Conclusions

We have systematically investigated the coding methods with combinations of multiple vibration parameters to convey attitude information. The results of the laboratory study show that our vibrotactile belt can achieve 91% localization accuracy and enable pilots to receive vibrotactile directional instructions with a resolution within 5°. Further work is required to validate this aspect in the context of our targeted application. A virtual environment equipped a VR helmet will be constructed to simulate flight. We will further test our tactile on a rotating room, where subjects can able to experience altered gravitoinertial acceleration (GIA). We will also improve coding strategies to cue integrated situation information for pilots with this vibrotactile vest. In summary, this work provide new evidence that the vest haptic displays have promised as an intuitive means of displaying navigation signals of aircraft and may improve spatial awareness in low visibility environments.

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