Evaluation of Tactile Drift Displays in Helicopter

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Abstract. Brownout during helicopter landing and takeoff is a serious problem and has caused numerous accidents. Development of displays indicating drift is one part of the solution, and since the visual modality is already saturated one possibility is to use a tactile display. The main purpose in this study was to investigate how tactile displays should be coded to maintain or increase the ability to control lateral drift. Two different tactile drift display configurations were compared, each with three different onset rates to indicate the speed of lateral drift. A visual drift display was used as control condition. The results show that best performance is obtained with the basic display with slow onset, and with complex display with constant onset rate. The results also showed that performance with the best tactile drift display configurations was equal to the already validated visual display.

Keywords: Tactile display, helicopter, brownout.

1 Background

Brownout caused by blowing sand is a serious problem for helicopter pilots. The main problem is limitations of visual references during takeoff and landing, which has led to numerous incidents [1]. The three main problems are lateral drift, difficulties of keeping heading to reference cue, and rate of closure. Lateral drift means that the helicopter drifts sideways without the pilot is noticing it. The consequences may be that the helicopter crashes against wires, a mountain side, or flips to the side during landing. Also, blowing sand may lead to the false perception that the helicopter moves in opposite direction. To remedy for this, at least three areas need attention: displays, sensors, and crew-cooperation. However, our focus is on tactile display solutions to compensate for lack of visual references. The basic idea with a tactile display is that the users (i.e. helicopter pilots) can receive tactile information and simultaneously look away from the instruments and instead look out the cockpit window to maintain orientation, look for obstacles on the ground in a landing situation, or keep track of the surrounding. Furthermore, pilots are in many situations already visually saturated.

Therefore, instead of adding further visual information, a tactile display may improve performance.

Alternative displays, such as tactile displays, can be useful both in military [9], [6] and civilian [2] situations. Furthermore, performance often improves when multimodal displays are used to simultaneously present redundant visual, tactile and auditory information. The idea of bimodal systems for simultaneous presentation of visual and auditory stimuli was proposed by [4]. Later Wickens [13-14] developed a theory called multiple resource theory (MRT). MRT [7], [15] describes our perceptual resources in four dimensions: modalities, stages, access, and responses that are represented in a cube. Risk for mental overload can be predicted by the amount of interference between information processing in the dimensions. A well designed multimodal display, i.e. distribution of the information between visual, tactile, and auditory channel, can improve performance and perhaps reduce mental workload.

In a helicopter study pilots were able to stay closer to a moving target during hover when using a tactile display (than without) and they also rated their situation awareness as higher when they used the tactile display [8]. Curry and Estrada [5] showed that a tactile belt significantly improved drift control during takeoff and hover in helicopters. For fatigued pilots (awake for 31 hours) drift control was significant better with than without a tactile belt. Even though tactile, bi- and multimodal displays are proven to improve performance compared to only visual displays, one question that need further attention is how to optimize the tactile pattern to improve performance further.

In both visual and tactile displays there is a need for good design, and to make sure that the user intuitively understands the information. Design of visual displays has a long tradition, but for tactile displays the design and evaluation of different tactile pattern or tactile messages are rather new, with exception of sensory impaired individuals. In military settings, efforts have been done, in i.e. soldier communication where design of tactile language and evaluation of tactile displays for dismounted soldiers [3],[12] proven to be useful.

Here we focus on tactile displays, and compare different tactile displays with each other and with a visual drift display for helicopter pilots. The main purpose was to investigate how tactile displays should be coded to maintain or increase the ability to control lateral drift. Two different tactile drift display configurations were compared, each with three different onset rates (frequencies) for indication of the speed of lateral drift. A previously validated visual drift display was used as control condition. To make sure that the visual and tactile display could be compared, they were coded in corresponding ways, i.e. make sure that perceptual momentum was achieved [10].

2 Method

2.1 Participants

14 participants without prior experience of flying a real or simulated helicopter participated in the experiment, five females and nine males. Their mean age was 24.1 years, with a standard deviation of 2.7 years.

2.2 Equipment

The simulation was performed with a PC-based simulation of a Bell 206B JetRanger helicopter, with Prepare 3D, an extension of Microsoft® Flight Simulator X. The surrounding graphics were presented on three 46-inch LED screens, with resolution 1920×1080 pixels. The three displays were placed in upright position with the left and right display slanted 28 degrees inward, and distance from the participants' eyes to the screen was approximately 110 centimeters. The primary head-down displays was the same as used in the instrumentation in a standard Bell 206B JetRanger and were presented on a 23-inch LCD touch display with resolution 1920×1080 pixels (Figure 1).

Fig. 1. Experimental setting with visual primary head-down display, and visual head-up drift display on the central screen

The simulator was controlled by joysticks and pedals, steering with a Flight Link G-stick III Plus Cyclic and a Flight Link Anti-Torque pedals, and throttle level by a Flight Link Collective throttle C1. The simulator was motion based with a MOOG Electric Motion Base MB-E-6DOF/12/1000 kg.

Three drift display configurations were used: visual drift display, tactile basic drift display, and tactile complex drift display. Also, for each tactile display configuration three different tactile patterns were used. The visual drift display was based on the hover display in a Seahawk helicopter, but was adapted at the Swedish Defence Research Agency (FOI), i.e. it only presented information about lateral drift, left or right, whereas the original hover display presents drift in all directions. In this experiment the visual drift display was presented head-up on the middle of the three 46-inch displays (Figure 2).

Speed of lateral drift, to the left or right, was indicated by a green vector. The length of the vector increased with the speed of lateral drift. When the drift was zero

(or below the threshold of 0.4 m/s) no vector was visible and only the green square in the center was visible. When lateral drift was 5 m/s the vector reached halfway to the white outline of the circle. When lateral drift was 10 m/s, or more, the vector reached the outline of the circle. In Figure 2 the vector indicates lateral drift to the left with 10 m/s or more.

Fig. 2. Visual drift display indicating lateral drift to the left with 10 m/s or more

The tactile drift displays (basic and complex) consisted of a tactile vest developed at the Swedish Defence Research Agency (FOI) with three rings of motor tactors (120 Hz) sewn-in the fabrics. Each ring has 12 motor tactors evenly positioned over the torso and one tactor is always positioned straight ahead. In this experiment only the middle ring was used. (Figure 3). For both the basic and complex displays the length of the pulses was 100 ms.

Fig. 3. Tactile vest

The tactile basic drift display only used two tactors, one tactor under each armpit. Drift was indicated by vibrations under the armpit, at the same side as the direction of the lateral drift, left (9 o'clock) or right (3 o'clock) with vibrating pulses. Analogously

to the visual drift display, when the drift was zero (or below the threshold of 0.4 m/s) the belt was silent, i.e. no vibrations were given.

The tactile complex lateral display used a more complex motion pattern and used all 12 tactors. Seven tactors were used for indication of drift to left and right respectively. The middle tactors (12 and 6 o'clock) were used both for the left and right drift indication pattern. The pattern indicated drift with pulses that alternated between the tactor under the armpit in the direction of the drift and to two other tactors, with a pause of 200 ms when shifting between tactors. When drift was zero (or below the threshold of 0.4 m/s the belt was silent, i.e. no vibrations were given. When lateral drift to the right exceeded 0.4 m/s the pulses alternated between the tactor under right armpit (3 o'clock) and the central tactors (12 and 6 o'clock simultaneously). When lateral drift to the right reached 1/3 of maximum indicated drift speed (1.67 m/s with fast onset and 3.33 m/s with constant and slow onset rates) the pulses changed to alternate between the tactor under right armpit (3 o'clock) and tactors 1 and 5 o'clock simultaneously. When lateral drift to the right reached 2/3 of maximum indicated drift (3.33 m/s with fast onset and 6.67 m/s with constant and slow onsets) the pulses alternated between the tactor under the right armpit (3 o'clock) and tactors 2 and 4 o'clock simultaneously. Drift to the left was presented analogously.

For both the tactile displays three different onset rates were used. At constant onset rate the interval between the pulses were always 2000 ms. At slow and fast onset rate the interval between the pulses decreases linearly from 2000 – 200 ms when the speed of the drift increased. When lateral drift started the interval between the pulses was 2000 ms, and when lateral drift was 10 m/s or more the interval between the pulses were 200 ms. At fast onset rate the minimal interval of the pulses (200 ms) was reached when lateral drift was 5 m/s or more. In other respect everything was identical to slow onset rate. This means that when the constant onset rate was used the basic display only gave information of direction of the drift, whereas the complex display gave information of both direction and speed of the drift. However, when the slow and fast onset rates were used the basic display gave information about both direction and speed of drift, and the complex display gave information of drift in two ways, both by the pattern and by the interval between the pulses (see Table 1).

Table 1. Types of information of lateral drift given by each tactile display configuration

	Direction of drift	Speed of drift by onset rate	Speed by tactile pattern
Basic constant onset	x		
Basic slow onset	x	x	
Basic fast onset	x	x	
Complex constant onset	x	x	
Complex slow onset	x	x	x
Complex fast onset	x	x	x

2.3 Design and Procedure

The experiment was performed with a within-subjects design with the two tactile lateral drift display conditions by the three onset rates. The visual drift display was used as a control condition. The order of the display configurations was balanced over participants. The participant's main task was to fly straight ahead and avoid lateral drift, and secondary to fly in a specific heading (north, south, west or east), at the altitude of 3000 feet, and with the speed of 30 knots.

Before the experiment started the participant received training, starting with a walkthrough about the functionality of the helicopter and the primary instruments (speed, altitude, compass, and gyro). The next phase was first free flight and then to fly at 3000 feet in 30 knots in a specified direction, analogously to how the task should be performed in the experiment. Then the participant learned the different drift displays, and made a test flight with each drift display configuration. The training continued until the experiment leader assessed that the participant had adequate control over the helicopter and fully understood the seven display configurations. The average training time was approximately one hour.

After the training was completed the experiment started. The participants tested each display configuration in turn (order depending on balancing). The duration of each display configuration was two minutes and was equally performed with all display configurations. After each display configuration the participant answered a questionnaire and after the last display configuration was completed the participant also answered a final questionnaire. Total time for the experiment, including training and instructions, was approximately 2 hours.

During each of the experimental conditions the experimental leader asked the participant to identify speed, altitude, and direction four times. The purpose was to make it necessary for the participant to avert the eyes from the displays and thereby increase the realism. The simulated weather conditions were good. The following performance measures were collected:

- Lateral drift – mean absolute lateral drift (m/s)
- Deviation of speed – mean absolute deviation from intended air speed of 30 knots (m/s).
- Deviation of altitude – mean deviation from intended altitude of 3000 feet (m).
- Deviation of heading – mean absolute deviation from the intended direction (degrees).

The reason for using the mean of the absolute values was to calculate the size of the deviation, i.e. the direction of the deviation was not important. All measures were logged with a sampling frequency of approximately 9 Hz. For each participant, in each display configurations, the mean was calculated from the absolute values of the sampling points.

The questionnaires mainly contained 7-point rating scales. Descriptions of analyzed questions are given in the Results.

3 Results

Data were analyzed with analysis of variance (ANOVA). In the case of violation of the sphericity assumption in the ANOVAs the Greenhouse-Geisser-corrected p -value is given. Post hoc testing was performed with Tukey's honestly significant difference (HSD) test.

3.1 Performance Measures

The performance measures of lateral drift, deviation of speed, deviation of altitude, and deviation of heading were each analyzed in two ways. First, a two-way factorial repeated measures ANOVA, 2 types of tactile displays (basic, complex) $\times$ 3 onset rates (constant, slow, fast) was used to investigate main and interaction effects of the tactile displays and the onset rates. Secondly, a one way repeated measures ANOVA was used to compare the 6 tactile display configurations with the visual drift display that was used as control condition. The reason for using separate ANOVAs is that there was only one type of coding of the visual drift display, thus main and interactions effects of tactile display configuration by onset rate could not be analyzed with the visual display included.

Lateral Drift. The two-way ANOVA showed a significant interaction effect of display by onset rate (Figure 4), $F(2, 26) = 8.13$, $p = .002$; but no main effects of display

Fig. 4. Mean lateral drift with the visual drift display and the two tactile drift displays with three onset rates

or onset rate. Post hoc testing showed significantly larger mean lateral drift for the basic display with constant onset compared to the complex display with constant onset rate ($p = .007$). Also, for the basic display lateral drift was significantly higher with constant compared to slow onset rate ($p = .041$), whereas for the complex display lateral drift was significantly lower with constant compared to fast onset rate ($p = .028$).

The one-way ANOVA only showed a strong tendency, $F(6, 78) = 3.00$, $p = .050$ of difference between the seven display configurations. Post hoc testing showed no significant differences between the visual display and the tactile display configurations.

Deviation in Speed. The ANOVAs showed no significant differences. The mean deviation from correct speed was 7.1 m/s.

Deviation in Altitude. The ANOVAs showed no significant differences. The mean deviation from correct altitude was 71.2 m.

Deviation in Heading. The ANOVAs showed no significant differences. The mean deviation from correct heading was 15.6 degrees.

3.2 Subjective Measures

The subjective ratings were analyzed in the same way as the performance data, one ANOVA was used to analyze main and interaction effects of two tactile display configuration and the three onset rates, and one ANOVA was used to analyze if there was any differences compared to the visual display configuration. However, since there were three questions about perception of lateral drift and two questions about disturbance of lateral drift, perception and disturbance of lateral drift were analyzed with a three-way repeated measures ANOVA, 2 types of tactile displays (basic, dynamic) $\times$ 3 onset rates (constant, slow, fast) $\times$ number of questions, to investigate main and interaction effects of the tactile displays and the onset rates, and a two-way ANOVA, 7 display configurations $\times$ number of questions, to compare the 6 tactile display configurations with the visual drift display.

Since there was only one question about mental workload, the analysis was equal to that of performance data, one two-way ANOVA to investigate main and interactions effects between the tactile displays and the onset rates, and one one-way ANOVA to compare the 6 tactile display configurations with the visual drift display.

Perception of Lateral Drift Presentation. The participants answered three rating questions about how they experienced the display information of lateral drift: perception, accuracy, and understanding of the drift information (1 = Very difficult – 7 = Very easy).

The three-way ANOVA only showed a significant main effect of onset rate, $F(2, 26) = 4.55$, $p = .020$. Post hoc testing showed that this was due to significantly higher ratings of how lateral drift was experienced at high onset rate ($M = 4.6$, $SE = 0.3$) compared to constant onset rate ($M = 3.9$, $SE = 0.2$) ($p = .016$).

The two-way ANOVA showed a significant main effect of display, $F(6, 78) = 5.28$, $p = .003$ (see Figure 5). Post hoc testing showed that the main effect of display was due to significantly higher ratings of the visual display ($M = 5.3$, $SE = 0.3$) compared to the basic tactile with both constant ($M = 3.4$, $SE = 0.3$) and slow onset rates ($M = 4.1$, $SE = 0.4$) ($ps < .001$). And also significantly lower ratings of the basic tactile display with constant onset rate compared to the complex tactile display with high onset rate ($M = 4.6$, $SE 0.3$) ($p = .047$).

Fig. 5. Subjective ratings for the visual display and the two tactile drift displays with three onset rates

Discomfort. The participants answered two rating questions about if the display presentation was experienced as disturbing: if it caused discomfort and if it was annoying (1 = Not at all – 7 = Very much). The ANOVAs showed no significant differences. The ratings of discomfort were very low ($M = 2.1$) per display configuration.

Mental Workload. The participants answered one rating question about how they experienced their mental workload (1 = Very low – 7 = Very high). The ANOVAs showed no significant differences. The ratings of mental workload were moderately high ($M = 4.8$).

4 Discussion

With the tactile basic display lateral drift was significantly better controlled with the slow onset rate compared to the constant onset rate. The reason that performance was worst with the constant onset rate is most likely that this display configuration gave no information of the speed of the drift. That performance was best with the slow onset rate (fast onset was not significantly better than constant) was most likely that the resolution of the drift information was higher with a slower onset rate.

With the tactile complex display lateral drift was significantly better controlled with the constant onset rate compared to the fast onset rate. The reason for the better performance with the constant onset rate is most likely that the dynamic pattern itself gave information of drift speed. Whereas, slow and fast onset rates that gave dual coding of lateral drift made the information more difficult to interpret.

There were no significant differences in control of drift between the tactile displays and the already validated visual drift displays. Although the tendency of the one-way ANOVA indicates differences between the displays, lateral drift with the two tactile displays which provided best control of drift were more or less equal to the visual display (see Figure 4).

Controlling altitude, speed, and heading were in a sense secondary tasks, and performance on these tasks, can thus also be regarded as secondary measures of mental workload. That these tasks were controlled equally well with the tactile drift displays as with the visual drift displays gives further support to the possibilities of using a tactile drift display. Furthermore, the ratings of workload, although relatively high were at the same level with the tactile and visual display configurations. Also, the participants did not experience the tactile displays as discomforting.

The subjective ratings of how the drift information was experienced are somewhat counterintuitive, since these ratings do not reflect the performance measures of lateral drift. For example the basic drift display with slow onset rate was rated lower than the visual display, but performance was comparable.

The results indicate that for the basic tactile display onset rate can successfully be used as a secondary information channel. Whereas, for a complex tactile display configuration that uses the tactile pattern to present speed information, the best alternative was to use the constant onset rate. It is interesting that performance with the complex tactile display, which only used three levels to indicate speed, when used with constant onset rate was equal to the tactile basic display with slow onset rate that presented speed information on a continuous scale. This indicates that if a tactile display is properly coded, speed information can be successfully coded with only a few levels.

That performance with the best tactile drift display configurations (basic with slow onset rate and complex with static onset rate) was equal to the already validated visual display supports the possibilities of using a tactile display. This also confirms results from our previous research that has shown that lateral drift, in principal, can be controlled equally well with both visual and tactile drift displays [11].

A fundamental idea with tactile displays is to make them intuitive, and the results here are important since they provide valuable information about how tactile patterns can be used to increase display interpretability and thereby decrease lateral drift. However, most likely a tactile display will be used together with a visual drift display,

in a bimodal drift display configuration. Therefore, further research is needed to investigate if a high level of perceptual momentum can be maintained when these suggested lateral tactile display configurations are used together with present visual display configurations.

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