Tactilient: Turbulence resilient tactile icons for pilot feedback

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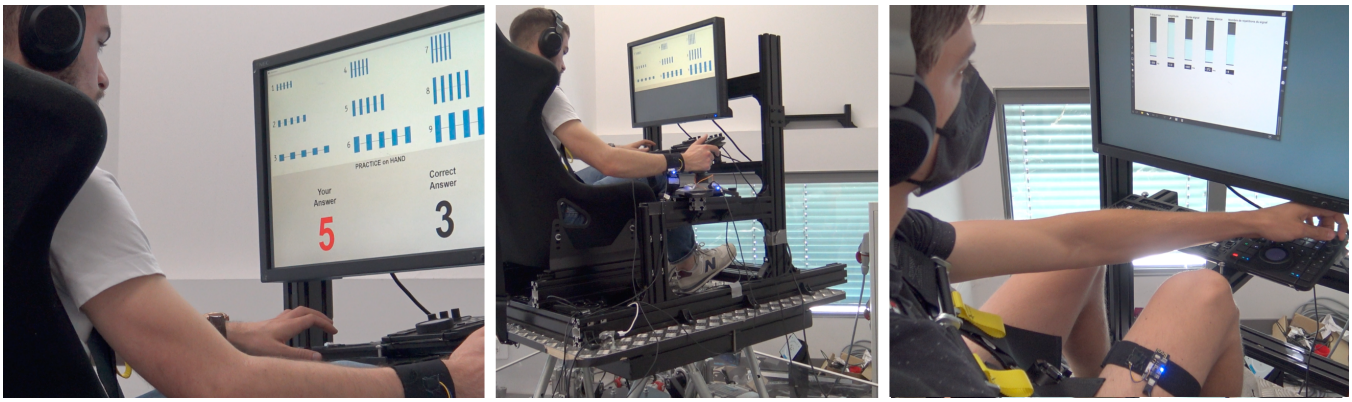

Figure 1: Overview of the study presented in the paper. Left: guided learning of vibrotactile patterns (tactons); Center: pattern recognition in turbulent conditions on a 6 DOF simulator; Right: design session of a vibrotactile pattern

ABSTRACT

Given the high attentional demand in aircraft cockpits, tactons can be used to deliver information without overloading the visual and auditory channels. However, aircraft are subject to turbulence that interfere with vibrotactile feedback. To investigate the impact of turbulence on tacton identification, 18 participants tried to identify 9 tactons with varying intensity and rhythm, while experiencing uncomfortable and very uncomfortable levels of mechanical vibration defined in ISO 2631-1. The results show that the effectiveness of tactile communication decreases with the rhythm identification performance as the level of turbulence increases. In our study, an RMS acceleration delta of 0.70 Grms between two consecutive tactons guaranteed near zero confusion. Based on their experience performing the study, participants built tactons that included 4 pulses, lasted for at least 350 ms and vibrated at no less than 1.25 Grms to be comfortably perceived. Our results will support practitioners for designing tactons that can be more resilient to turbulence.

CCS CONCEPTS

• **Human-centered computing** → **Interaction techniques**; Haptic devices.

KEYWORDS

turbulence, tactile feedback, aviation, haptics

*Both authors contributed equally to this research.

1 INTRODUCTION

Piloting an aircraft is a highly complex task that requires visual and auditory attention. For instance, pilots constantly collect visual information through the cockpit windows and from the numerous cockpit instruments to monitor the current flight status and ensure flight safety [44, 45]. Auditory warnings and vocal communications with other pilots and air traffic controllers provide further critical information that contribute to flight safety [19, 34]. As flight support technology and aircraft capabilities advance, the quantity of information available to pilots always increases [35].

Vibrotactile feedback can deliver information to pilots without burdening the visual and auditory channels. For example, it can be used for delivering information on aircraft surroundings, on aircraft status or on critical situations when immediate action is required [17, 37, 49]. Although contributions studying vibrotactile feedback in the cockpit show promising results, most of the research has provided designs that have been evaluated through static simulations exempted from motion. However, turbulence lead to aircraft oscillatory motions that propagate to the aircraft cockpit and the pilots [30]. Turbulence also propagate to pilots' bodies, creating unexpected whole-body vibrations that can be detrimental to the interaction with the cockpit instruments. Accidental touches and the lack of tactile and aural feedback may lead to command errors on touchscreens, which is worsened by turbulent conditions [13]. Prior research has found that as the level of turbulence increases, touch input performance decreases [11].

Outside the context of aeronautics, there is evidence that turbulence may also affect vibrotactile feedback. For instance, when used to reduce sensory impairment, whole-body vibration training has been found to temporarily degrade tactile sensitivity [41]. Other research has found that ambient vibration in cars can mask low frequency vibrotactile patterns [21]. To our knowledge, the effect of flight turbulence on the perception of vibrotactile patterns in the cockpit has not been studied yet.

In this paper, we investigated the effect of turbulence on vibrotactile pattern identification. We conducted a study to examine the users' capacities to identify vibrotactile patterns at different mechanical vibration levels (Figure 1). A motion platform was used to induce mechanical vibrations and expose participants to three levels of simulated turbulence based on ISO standard 2631-1 [20]: none, uncomfortable and very uncomfortable. While experiencing turbulence, participants were asked to identify nine different patterns built according to the recommendations from the literature on designing tactons (i.e., abstract tactile messages defined by a set of parameters such as frequency, amplitude, duration or rhythm that communicate meaningful information to users non-visually [4]). Based on their experiences acquired during the experiment and their subjective preferences, participants designed tactons that they could comfortably perceive during turbulence. Our results reveal that the identification performance decreases as the level of turbulence increases, and that a RMS acceleration delta of 0.7 Grms between two consecutive tactons is needed to avoid any confusion. Furthermore, to be comfortably perceived, tactons should last at least for 350 ms and vibrate at no less than 1.25 Grms.

Our contribution is quadruple. First, we provide empirical data on user performance for vibrotactile pattern identification during turbulence. Second, we identify how turbulence affect each parameter used to design the tactons in our study. We then identify the best parameter values to provide tactons that can be comfortably perceived by participants. Finally, we provide recommendations to support practitioners designing tactons that are more resilient to turbulence.

2 RELATED WORK

Our work draws motivation from different research areas. In this section, we first cover the research about supporting pilots for flying safely through vibrotactile feedback. Then, we look into the design foundations of vibrotactile pattern feedback in the literature. Finally, we discuss the research on interaction design in the context of turbulence.

2.1 Vibrotactile feedback for pilots

Researchers have proposed various vibrotactile designs to assist pilots for spatial orientation awareness [37, 38, 50], controlling flight parameters [17, 28, 58] or flight situation awareness [16, 36, 40, 49].

Rupert *et al.* conducted a series of in-flight studies that demonstrate the effectiveness of vibrotactile feedback in cockpits [37]. For example, using matrices of 8×3 and 8×5 actuators sewed on a vest, they were able to communicate situation awareness information to jet pilots such as the gravity vector direction. Additional research using off-the-shelf tactors [53] lead to the design of more powerful actuators capable of providing signals resilient to the high noise and vibration aviation environment, and perceivable by pilots while flying [37].

Using a vibrotactile display as an aircraft pilot's spatial disorientation countermeasure, van Erp *et al.* investigated the best vibrotactile parameters for depicting rotational information and the most appropriate time to trigger the feedback [50]. In their study, participants wore a vibrotactile vest made of 48 actuators vibrating at 150hz. Each stimulus consisted in two actuators vibrating at the same time to indicate the direction of the rotation. Their results show that such patterns were powerful enough to overrule the errors pilots made following the orientation cues from their vestibular sense.

However, the torso is not the most sensitive body part to vibrotactile stimuli and other body locations may be suitable for tactile feedback in the cockpit [51]. Salzer *et al.* investigated tactile feedback on the thigh to communicate directional cues to pilots [40]. In a vibration localisation task, they compared continuous and pulsed patterns at 250Hz. They observed that in seated positions the upper and the bottom most tactors were the most accurate, reaction time was fastest for continuous signals and the longest signals yielded the best accuracy.

In Tippey and colleagues' study, weather alerts were delivered to the wrist [49]. Comparing continuous vibration and pulsed vibration alerts, they observed that vibrations on the wrist are effective in attracting attention, even though the participants could not discriminate the different pulsed signals used to characterise alert urgency. Moreover, pilots were able to feel the vibrations during in-flight testing.

Zikmund *et al.* investigated the use of vibrotactile feedback on a joystick to help pilots maintain the aircraft's angle of attack [58]. To guide users into pushing or pulling the stick, their prototype included two actuators located at the front and the back of the device, delivering pulsed patterns whose rhythm increased with the closeness to the angle target. Their findings show that vibrations were useful for precise positioning, delivering clear and short signals to stay within tolerance.

Although all contributions have proposed efficient vibrotactile techniques to support specific tasks, the feedback characteristics and parameters differ from one design to another. Therefore, to better understand how to design efficient vibrotactile patterns, we survey the foundations of vibrotactile feedback design.

2.2 Vibrotactile feedback design

Tactons or tactile icons are structured abstract messages defined by a set of parameters such as frequency, amplitude, duration or rhythm that communicate meaningful information to users non-visually [4]. Given the high demand of visual and auditory information in the cockpit, tactons have the potential to lower the mental demand for processing the information through the visual and auditory sensory channel alone [27]. Although tacton structures can be very sophisticated especially in their compound forms [4], they should be easily identifiable by pilots to provide an additional useful information channel. In this paper, we therefore start to investigate multidimensional tactons delivered on a single actuator.

Prior research has investigated how to optimise the detection and identification of tactons. For instance, number of pulses and

duration have proven to be significant parameters to design tactons [6, 7]. In an experiment in which participants had to identify the level of urgency and the type of message through tactons delivered to their index finger, Brown *et al.* observed that rhythm (number of pulses and duration) was a better parameter to encode information in tactons than signal modulation [6]. This was confirmed in a follow-up experiment in which similar tactons were delivered on different locations on the forearm [7].

High frequencies, strong amplitudes and long duration may facilitate tacton identification. Azadi and Jones [2, 3] conducted experiments in which vibrotactile patterns that varied in amplitude, frequency and pulse duration were played on the index finger and the forearm in an identification task. In these studies, the vibrotactile patterns were designed with redundant frequencies and amplitudes to facilitate the tacton identification. Using two levels of frequency and two levels of amplitude, tactons with higher frequency and stronger amplitude were found easier to identify than tactons with lower frequency and weaker amplitude [2]. Adding a third frequency level, tactons were better identified when presented on the forearm rather than on the finger, and short low-frequency patterns were more difficult to recognise than long high frequency patterns [3]. In a study that investigated tacton design for the car, it was found that the 6 most distinguishable tactons among a set of 18 had a frequency of either 80 or 250 Hz and a duration of either 0.5 or 2 seconds [21].

Inter-pulse interval design can improve tacton detection. In a study which investigates the effect of signal waveform, envelope and inter-pulse intervals on tacton detection, Chancey *et al.* discovered that among 27 tactons the ones with shorter inter-pulse interval yielded shorter reaction times [9]. Although this result is affected by the signal envelope and waveform, the authors recommend considering inter-pulse interval when designing alarm signals. That being said, rhythm may be difficult to recognise for tactons with low frequencies and amplitudes [3].

It is worth noting that the amount of information that tactons may convey from a single actuator has been quantified [3, 10, 57]. By measuring the information transfer (IT), a generic measure of the amount of information provided by a communication signal, Chen *et al.* reported an IT of 2.73 bits in a tacton identification study including 60 stimuli simulating various virtual mobile phone key clicks [10]. In other words, participants could correctly identify between six and seven tactons varying in amplitude, frequency and number of cycles (i.e. pulse). With nine tactons in which inter-pulse intervals varied with time, Azadi and Jones found an average of 2.43 bits and 2.34 bits when tactons were delivered to the index finger and to the forearm respectively [3], resulting in identifying 5.39 respectively 5.02 patterns on average. Delivering 90 tactons on the wrist which varied in tempo, number of pulses, frequency and amplitude, Yoo *et al.* measured an average IT of 3.065 bits resulting in 8 to 9 tactons correctly identified [57]. Their findings also reveal that frequency and amplitude were not the most effective parameters to deliver information.

Although these studies provide information for designing efficient tactons, their findings are only relevant when users' bodies are still. Whole-body vibrations affect vibrotactile feedback detection [18]. For instance, vibrotactile stimuli detection performance decreases when users are walking [22]. Some research has also found that foot tactile sensitivity degrades after being exposed to horizontal whole-body vibrations during 4 minutes [41]. In another study, Ryu *et al.* have found that vibrotactile feedback in the car should not be designed with a frequency lower than 60Hz to avoid any temporal masking by the ambient vibration [21]. In aircraft, pilots are exposed to oscillatory motions caused by air disturbances in which the aircraft is flying, resulting in whole-body vibration [30].

To sum up, tactons should be easier to identify when they have high frequencies, strong amplitudes and long duration. Besides, inter-pulse interval design is also key for tactons identification. While these recommendations are valid when the body is still, it is unclear whether classical tacton design can be applied for communicating information in the aircraft cockpit and how many tactons can be correctly identified under turbulence. In the next section, we cover the research about designing interaction for contexts with turbulence.

2.3 Interaction in turbulent spaces

The impact of context displacements (turbulence, vibrations, accelerations, etc.) on user performance has been extensively studied for input control [11, 14, 25, 31, 39, 46] and relatively little for perception [51, 58].

To mitigate the effect of the aircraft cockpit displacements on touch input, Cockburn *et al.* demonstrated that a physical guide on a touchscreen can improve accuracy for small targets in high turbulence situations [11]. Three turbulence contexts (none, low, and high) were simulated by a motion platform mounted on a hexapod. Following ISO 2631-1 recommendations, which provide methods for evaluating the human exposure to whole-body vibrations, the platform produced non-periodic vertical displacements with an average motion frequency of 3.1 Hz (max 5 Hz) and weighted average accelerations from 0.8 m/s2 to 2.6 m/s2 [20].

In another study on input devices, Lin *et al.* compared the influence of ship motion on touchscreens, mice, and trackballs [25]. In their study, the level of low-frequency motion was set to a root-mean-square (RMS) acceleration of 0.34 m/s^2, which corresponds to the "somewhat uncomfortable" rating in the ISO discomfort index (ISO 2631-1). The study shows that under vibration, although the performance degraded for the touchscreen, it remained stable for the mouse. These performance issues are confirmed by Dodd *et al.* who demonstrated a strong impact of turbulence at high altitudes (8000 feet) on tactile interaction [14]. Furthermore, Suijkerbuijk *et al.* found that when using a tactile flight display to change heading, level, or speed parameters, cognitive load increased strongly during turbulences [46]. Finally, Le Pape and Vatrapu demonstrated that the acceleration force (G-force) had a significant impact on the usability of touch screens and this as early as $1G$ on the vertical up-down axis ($+1Gz$) [23], which was confirmed in an ecological environment by Avsar *et al.* [1].

The impacts of context displacements on the vibratory haptic feedback perception in aviation have been little studied for the moment. Van Veen and Van Erp were interested in the influence of high G-loads (up to $6G$) on the perception of vibrotactile stimuli on the torso [51]. They concluded that continuous accelerations perceived in an airplane in flight do not influence the perception

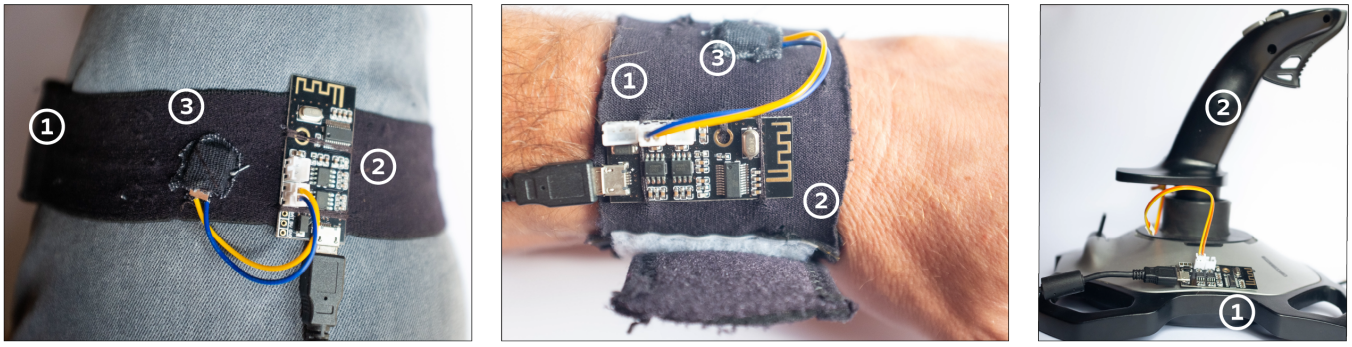

Figure 2: The output devices used in the study. The thighband (left) and the wristband (center) with the DFrobot audio card (2) and the Vybronics motor (3) attached to the neoprene band (1); the flight stick with the DFrobot audio card (1) and the Vybronics motor (2) integrated inside the plastic shell (right)

of vibrotactile signals. However, this type of acceleration does not match the vibrations felt in turbulence.

Zikmund *et al.* conducted a study in flight conditions in a small aircraft to estimate the usability of haptic feedback on the rudder and control column to indicate skidding. The perception of the vibrotactile signals was not masked by environmental vibrations [58]. Nevertheless, the study did not focus on turbulence, but only on vibrations induced by the operation of the engines. Moreover, no measurement of neither the vibration forces nor the vibrotactile feedback was reported.

2.4 Summary and conclusion

While many scientific studies have focused on understanding the impact of turbulence on input control, the question of the whole-body vibration effects on the perception and identification of vibrotactile patterns (tactons) has not yet been addressed. According to the literature, turbulence is undoubtedly detrimental to input performance. However, little is known on its effect on vibrotactile feedback in aviation. Furthermore, research on designing tactile feedback for the cockpit is scarce. Therefore, in this paper, we aim at addressing the following research questions to support the design of efficient vibrotactile patterns for the aviation domain:

- (Q1) Does turbulence affect vibrotactile pattern identification?
- (Q2) Can we design vibrotactile patterns that are resilient to turbulence?

3 INVESTIGATING THE IMPACT OF TURBULENCE ON VIBROTACTILE PATTERN IDENTIFICATION

We conducted a study to understand the influence of whole-body vibration caused by turbulence on vibrotactile feedback. First, participants had to complete a series of vibrotactile pattern identification on different body locations (hand, wrist and thigh) while experiencing different levels of turbulence (no turbulence, uncomfortable and very uncomfortable). The absence of turbulence served as a baseline for comparison with the other two levels to examine the effect of turbulence on vibrotactile perception. Then, upon completion of the identification tasks, participants were asked to design an optimal tacton that would be resilient to the turbulence they just had experienced.

3.1 Study Design

The literature reports different levels of sensitivity to tactile sensation throughout the body [12]. Consequently, we wanted to examine whether a potential effect of turbulence on tacton identification would be consistent across different locations of the body. In our study, tactile feedback was delivered through 3 actuators to stimulate the different parts of the body (Figure 2). Two of them were mounted in a neoprene band, which was attached to the wrist respectively the thigh. The third one was mounted inside a flight stick (joystick), which was hold by participants' right hand during the experiment. The locations were chosen according to the literature on vibrotactile feedback in the aviation.

Based on the work of Azadi and Jones [2, 3], nine patterns were designed, which varied in frequency, pulse and duration (Figure 3). These tacton configurations allowed us to cover most of the tactile sensitivity space. Since the frequencies used in [3] did not yield acceptable identification performance in our pilot study, we selected frequencies of 30, 120 and 210 Hz in our design. These values remain in the 30-300 Hz band, for which the mechanoreceptive system of the skin is very sensitive [32]. Each of the tactons was presented with 5 pulses and one of these 3 rhythms: 140 ms pulses with 75 ms inter-pulse intervals (IPI), 210 ms pulses with 112 ms IPI, 350 ms pulses with 187 ms IPI. They lasted for 1, 1.5 and 2.5 s respectively. All the tactons from T1 to T9 and their characteristics are illustrated in Figure 3. As in [3], a visual representation of the tactons was displayed at all times to circumvent the tactons memorisation. Pilot studies were conducted to ensure that these tactons were recognisable. In the absence of turbulence, identification success rates reached over 60% across all body locations after 15 minutes of training.

Finally, we measured the root-mean-square (RMS) acceleration for each device at the three frequencies and amplitude used in our study for the sake of reproducibility and discussion. Off-the-shelf affordable but efficient and popular actuators were used for our study [52]. The amplitude was set to maximum level available on our system for all tactons. The wristband vibrated at 0.6, 1.05 and

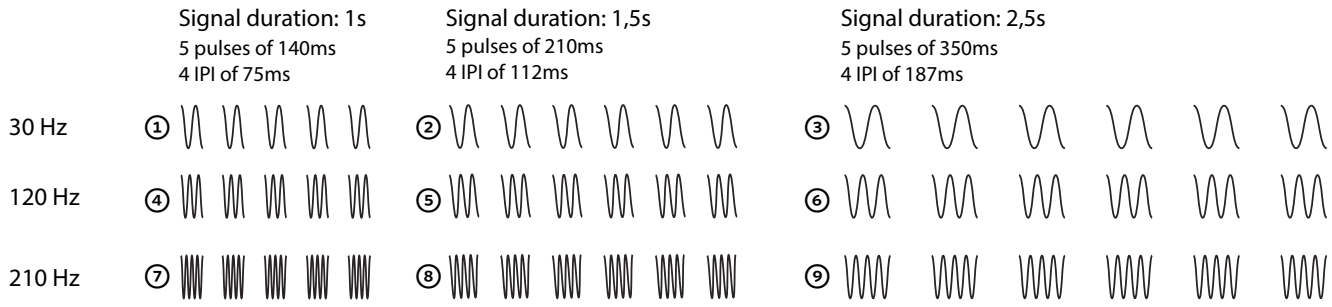

Figure 3: The set of nine tactons (T1 to T9) with the three frequency levels and the three vibratory patterns used in the study.

1.30 Grms for 30, 120 and 210 Hz, respectively. The thigh band vibrated at 0.45, 0.75 and 1.25 Grms for 30, 120 and 210 Hz, respectively. The flight stick vibrated at 0.1, 0.14 and 0.35 Grms for 30, 120 and 210 Hz, respectively.

As in prior work [11, 25], turbulence were induced by a motion platform following the definitions of mechanical vibrations in ISO2631-1 standard [20]. These definitions suggest weighted effective accelerations in the ranges of $0.8 < a_T < 1.6\ m/s^2$ for "uncomfortable" and $1.25 < a_T < 2.5\ m/s^2$ for "very uncomfortable" mechanical vibration.

To allow the comparison between the different levels of turbulence, we measured the tacton identification performance through identification success rate and trial duration. In addition, we also measured the amount of information conveyed by tactons for each condition through information transfer (IT) [47]. As explained in the related work section, IT describes the quantity of information that can be distinguished from the set of vibrotactile patterns and the maximum number of tactons that can be identified by the participants [3]. Information transfer is useful for characterising performance when the tasks involve the correct identification of one stimulus from a set of alternatives [47].

The goals of the study were: (1) to compare and investigate users' tacton identification performance for each stimulated location of the body (wrist, thigh, hand) and each level of turbulence (none, uncomfortable, very uncomfortable), (2) to identify parameter values that could make tactons resilient to turbulence. Based on previous research, we formulated four hypotheses to investigate:

- H1: Turbulence will decrease vibrotactile pattern identification performance [21, 22]
- H2: Turbulence will decrease the quantity of information conveyed by vibrotactile patterns [3, 10, 57]
- H3: Turbulence will not affect the identification performance of vibrotactile patterns with high frequency and long pulse duration [3, 21].
- H4: Turbulence will affect vibrotactile pattern rhythm less than frequency and amplitude [6, 7]

To summarise, our within-subject study had two independent variables: *turbulence* and body *location*. *Turbulence* had three levels: *no turbulence* (*NT*), *uncomfortable* (*UT*) and *very uncomfortable* (*VUT*). There were also three levels for the variable *location*: *hand*, *wrist* and *thigh*. There were also nine tactons to identify with the same amplitude and number of pulses but with varying frequency, pulse duration and inter-pulse interval duration (Figure 3). Tactons' *frequency* was either *low* (30Hz), *medium* (120Hz) or *high* (210Hz). Tactons' rhythm was also tied to the tactons' total duration. Tactons' *rhythm* was either *fast* (1s duration), *medium* (1.5s duration) or *slow* (2.5s duration). Finally, our study had three dependent variables: identification success rate, identification duration and information transfer.

3.2 Participants

18 volunteers with no sensory impairment (16 males, 2 females) aged between 22 and 44 years (M=27.11, SD=7.68) were recruited from local institutions. Four of them were licensed pilots. Three participants had never experienced vibrotactile feedback, while the others were familiar with mobile phone notifications.

3.3 Procedure

Upon completing a consent form and demographic questionnaire, participants were seated and securely fastened in our simulation platform. The experimenter then equipped the participants with the vibrating bands containing the actuators and a pair of noise-cancelling headphones. Participants adjusted the bands at the beginning of the experiment by positioning the actuators on the top side of the thigh and of the wrist before tightening them. A flight stick was accessible to participants' right hand and was to hold when instructed. The headphones were used to play pink noise during the experiment to cover any sound from the vibrating devices.

The experiment began with a training session in *no turbulence* condition (*NT*). It was divided into three series, with one for each device. In each series, nine tactons were first played in ascending order on the device. Then, participants were asked to identify all tactons presented in a random order. To make a selection, the participants had to press the key on the keyboard corresponding to the tacton's number on the visual representation displayed on the screen (Figure 4). The tactons' properties were displayed at all times during the study. The keyboard had only nine keys that were spread over the keyboard surface to avoid typing errors due to turbulence. Once the participant pressed a key, the trial ended and the system displayed the correct answer. Feedback was provided only in the training phase. When the participants felt comfortable with the stimuli and the identification procedure, the identification task started.

Figure 4: Experimental setup. Left: The 6 DOF motion platform ; Center: the experimental environment with a keyboard to indicate the number of the tacton (1), a Loupeddeck CT pad for the design part (2), the screen (3) with the diagrams of the tactons and the anti-noise headphones (4) ; Right: the information screen during the training phase.

The main task included nine series of 27 randomly played tactons to identify, corresponding to the conditions of the experiment (*turbulence* × *location*). The orders of the turbulence levels and the output locations were counterbalanced using a latin square design. Participant were told to answer as quickly as possible as soon as the stimulus has ended. The elapsed time between the end of the stimulus presentation and the participants' key input was recorded as the trial duration time. We also recorded participants' answers to measure the identification success rate. The trial was considered an identification failure if the participant did not make any selection within 10 seconds. Every time the output location changed, a warm-up series was played to ensure the proper functioning of the vibrating device. A break was offered to participants between each condition.

Following the identification task, the participants were asked to design their own tacton. Starting from the tacton with the *medium frequency* and *medium rhythm* presented on one of the three vibrating devices of their choice in *no turbulence (NT)*, they could vary frequency, amplitude, pulse duration and inter-pulse interval duration as they experienced the vibrotactile pattern. They then had the opportunity to edit their design under *uncomfortable (UT)* and *very uncomfortable turbulence (VUT)* until they were satisfied.

At the end of the experiment, participants filled a questionnaire that evaluated their subjective opinion on the turbulence realism and the tactons we had designed, and collected qualitative data on their own tacton design. Finally, participants were asked to reflect on the use of the tactons to encode the level of urgency of tactile alerts. The turbulence simulation lasted for about 60 minutes including participants' breaks.

3.4 Apparatus

Turbulence were simulated by a six degrees of freedom (6DOF) platform composed of six 3-phase 2.2 kw motors (1500 rpm, 243 Nm) connected to a Thanos Motion Simulator Electronics AMC1280USB board (Figure 4). The architecture of the structure allowed maximum displacements of ±30 cm on the heave, sway and surge axes, ±15° on pitch, roll and yaw angles and maximum accelerations of 1*G*. The motion platform was driven by X-Sim, a software made for piloting commercial 6DOF simulators [56].

As in Cockburn *et al.*'s study, the motion pattern sent to the platform was designed to induce non-periodic vertical displacements with a mean motion frequency of 2.51 Hz [11]. However, the motion frequency was lower than the motion frequency of air turbulence during the cruise phase reported in [25]. Measured accelerations from the surface of the motion platform for heave, sway and surge were 1.2, 0.2, and 0.1 m/s^2 respectively for uncomfortable turbulence, and 2.12, 0.7 and 0.25 m/s^2 respectively for very uncomfortable turbulence. These values are in line with the uncomfortable and very uncomfortable ranges reported by ISO 2631-1 [20].

The tactons were generated into wave files (mono, 44100 Hz, 32 bits) and converted into vibrations to the actuators by TI DRV2605 driver boards. Max 8 from Cycling '74 was used to visualise and edit the tactons parameters in real time by the participants.

A 24" NEC EA241WM screen display was mounted on the motion platform structure at about 50 cm from the user, with the upper edge of the screen about 15 cm below the eye line. The screen was used to display the nine tactons' characteristics at all times, and the correct answer in the tacton identification training phase only. During the design phase, the display informed participants on the tacton's current settings they were manipulating.

Two keyboards placed under the screen were used to collect data input from participants. As mentioned previously, a 9-key keyboard was used to collect participants' answers during the identification task. A Loupedeck CT console was used to explore tacton parameters [26]. The rotary physical knobs allowed a better control of the parameters under turbulence.

Three vibrating devices, a wristband, a thighband and a flight stick, were built for each output location (Figure 2). All three devices integrated the same VLV101040A wideband LRA actuators from Vybronics [52]. Two actuators were sewn onto the wristband and the thighband, which were made of 3mm thick neoprene fabric (Figure 2). Finally, an actuator was glued onto the plastic shell inside a Logitech G Extreme 3D Pro Joystick, which delivered vibration to the right hand. Each output device was connected to a DFR0720

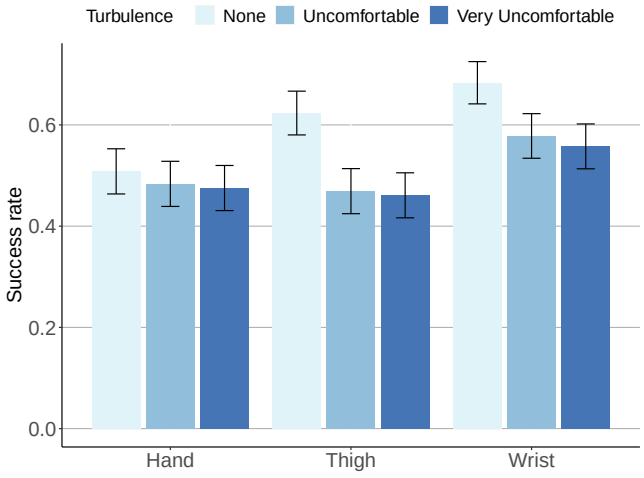

Figure 5: Tacton identification success rate by *location* × *turbulence*. Error bars denote the 95% confidence interval.

DFrobot sound card connected via USB to the experiment's control PC.

An application was designed to run the experiment. It was developed in Python 3.8 and PyQt5 and ran on an Intel Core i9 3.7GHz desktop computer. The application allowed us to play the wave files containing the tactons on the output devices and to send the turbulence data to the X-Sim motion platform control software. The application also logged all data from participants during the identification task. In addition, our application communicated with Max 8 to update the tacton settings in the design session and collect data from participants' designs. All communications between our application, X-Sim and Max 8 were made through UDP.

Finally, a pair of Jabra Elite 85h bluetooth noise-cancelling headphones was used to deliver pink noise to participants' ears, allowing to cover the sound of the vibrating devices.

4 RESULTS

We collected a total of 4374 trials across all conditions from the 18 participants.

4.1 Tacton identification

The tacton identification mean success rate was the lowest for all the output locations when the participants experienced the *very uncomfortable* turbulence. The success rates are reported in Table 1 and illustrated in Figure 5. An aligned rank transform (ART) was performed on the data to accommodate the non-parametric nature of the data distribution before further analysis [55]. An ANOVA on the transformed data revealed a significant main effect of *turbulence* ($F_{2,136} = 13.135$, $p < .0001$) and a significant effect of *location* ($F_{2,136} = 16.041$, $p < .0001$) for success rate. No other significant effect was found.

As the intensity of turbulence increased, the identification duration (i.e. time between the end of the stimuli and the user input) increased for stimulation on the *thigh* and on the *wrist*. All results are reported in Table 1 and illustrated in Figure 6. An ART was performed on the data. An ANOVA on the transformed data revealed a significant main effect of the *turbulence* ($F_{2,136} = 13.7796$, $p < .0001$) and a significant interaction of *location* and *turbulence* ($F_{4,136} = 3.2120$, $p < .05$) for duration. Post-hoc ART-C comparisons [15] showed that identifying vibrotactile patterns on the *thigh* in *NT* was significantly faster than on the *thigh* ($t(136) = -4.756$, $p < .001$) and on the *wrist* ($th(136) = -3.615$, $p < .05$) in *UT*. Furthermore, it was significantly faster than on the *thigh* ($t(136) = -4.43$, $p < .0001$) and on the *wrist* ($t(136) = -3.678$, $p < .05$) in *VUT*. Finally, identifying vibratory patterns on the *wrist* in *NT* was significantly faster than on the *thigh* ($t(136) = -4.456$, $p < .0001$) and on the *wrist* ($t(136) = -3.315$, $p < .05$) in *UT*, and significantly faster than on the *thigh* ($t(136) = -4.131$, $p < .005$) and on the wrist ($t(136) = -3.379$, $p < .05$) in *VUT*.

4.2 Communication efficiency

To assess the communication efficiency across turbulence levels, we measured the information transfer (IT) [47]. For each participant, output location and turbulence level, a confusion matrix was computed from each stimulus-response pair and the average IT and the quantity of information in the stimuli was calculated [2, 3, 47].

From a set of 9 tactons to be identified, the total quantity of information that could be transferred (i.e. the total quantity of information contained per stimulus) was 3.17 bits [3]. Across all locations, the mean IT was 2.3 bits ($SD = 0.33$) in *NT*, 2.17 bits ($SD = 0.28$) in *UT* and 2.1 bits ($SD = 0.29$) in *VUT*. In other words, participants were able to identify 4.9, 4.5 and 4.29 patterns in *NT*, *UT* and *VUT* respectively.

For each location, the highest IT was found for *NT* while the lowest IT was found for *VUT*. All values are reported in Table 1 and results are illustrated in Figure 7. A repeated-measure two-way ANOVA revealed a significant effect of *turbulence* ($F_{2,153} = 6.842$, $p < .01$) and *location* ($F_{2,153} = 7.885$, $p < .0001$), but no interaction.

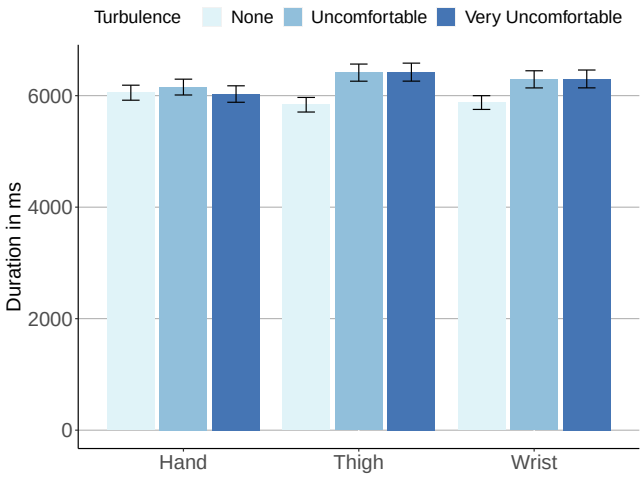

Figure 6: Tacton identification duration in ms by *location* × *turbulence*. Error bars denote the 95% confidence interval.

Table 1: Tacton identification mean and standard deviation for success rate, identification duration (in ms) and information transfer estimation (in bits), and number of patterns identified.

Location	Turbulence	Success	SD	Duration	SD	IT	SD	Tacton
Hand	None	0.51	0.50	6053	1510	2.14	0.32	4.41
	Uncomfortable	0.48	0.50	6154	1592	2.13	0.33	4.39
	Very Uncomfortable	0.48	0.50	6029	1657	2.02	0.29	4.06
Thigh	None	0.62	0.49	5837	1468	2.31	0.31	4.97
	Uncomfortable	0.47	0.50	6413	1724	2.11	0.21	4.31
	Very Uncomfortable	0.47	0.50	6422	1811	2.05	0.32	4.14
Wrist	None	0.68	0.47	5876	1376	2.45	0.31	5.45
	Uncomfortable	0.58	0.49	6292	1725	2.27	0.26	4.83
	Very Uncomfortable	0.56	0.50	6300	1796	2.22	0.21	4.65

4.3 Tacton identification errors

To understand the nature of the errors introduced by turbulence, we analysed the confusion matrices of participants' responses in *NT* and *VUT*. These matrices include responses across all output *locations*. The confusion matrices are presented in Figure 8.

In both matrices, we found zero or low confusion values between tactons T1, T2, T3 and T7, T8, T9. This indicates that there was little confusion between tactons with *low* and *high* frequencies, regardless of the rhythm. In addition, we noticed more confusion for tacton T7 and T8 than T9, and for T4 and T5 than T6. Within a same frequency, tactons with the slowest rhythm were less mistaken.

From *NT* to *VUT*, a growth of response absences (-1) was observed, especially for tactons T1 and T2, which both vibrated at the *low* frequency. In addition, some confusion between tactons T6 and T9 or T4, T5 and T8 or T2 was observed in *NT*. This indicated that tactons with a *medium* and a *fast* rhythm were confused with tactons with a similar rhythm but a different frequency. In *VUT*, this pattern was observed to a lesser extent. As a matter of fact, tacton T5 was also confused with T6 or T4 spreading errors to *rhythm* as well.

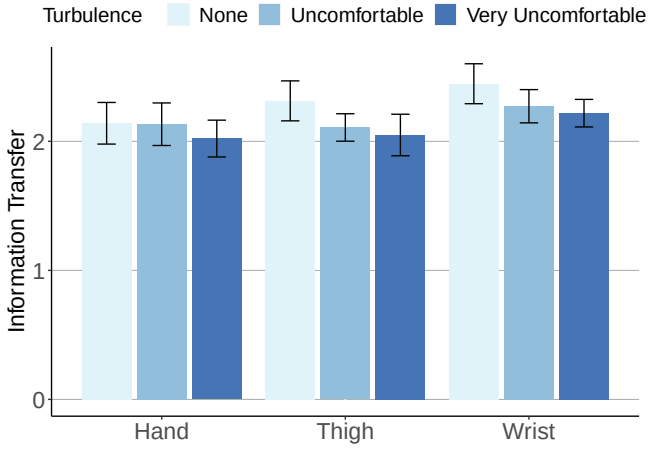

Figure 7: Tacton information transfer in bits by *location* × *turbulence*. Error bars denote the 95% confidence interval.

4.4 Users' defined tactons

More than 70% of participants configured their tacton with a frequency higher than 200Hz across all devices. Median frequency for each device was 212.5 Hz, which was very close to the *high* frequency level in our experiment. The maximum frequency recommended by the participants was 300 Hz for the *wrist*, 445 Hz for the *thigh* and 390 Hz for the *hand* (Figure 9). On the *wrist* and on the *hand*, participants was more inclined to set a value higher than our *high* frequency setting.

Participants tended to significantly increase the pulse and inter-pulse interval durations from the *slow* tactons (T3, T6, T9) proposed in our experiment. With median pulse durations of 520 ms, 545 ms, and 470 ms for the *wrist*, the *thigh* and the *hand*, the settings were 48%, 56% and 29% respectively longer than the longest pulse duration in our experiment (350 ms). It was similar for inter-pulse intervals, with median durations of 247 ms, 222 ms and 262 ms for the *wrist*, the *thigh* and the *hand*, which in turn were respectively 32%, 19% and 40% respectively longer than the inter-pulse interval duration of our slowest tacton (187 ms). Finally, the participants recommended four pulses which is slightly less than our original tacton design.

4.5 Realism and subjective preferences

Almost all participants agreed that the sensations felt on the platform were similar to those felt during real turbulence. One of the participants with flying experience found "the reproduction of turbulence very accurate". Almost half of the participants felt some discomfort in *UT* and two third in *VUT*.

Overall, the subjective data show that the difficulty to identify tacton increased from T9 to T1. Identifying tactons was difficult for 6 participants who thought they had missed some stimuli. While all participants found T9 the easiest tacton to identify, they also found T2 difficult to identify. Participants also thought that within the same frequency, the tacton with the *slow* rhythm was the easiest to identity. Dynamic variation of parameters combination was suggested to improve the tacton discernibility: "Varying the amplitude and frequency of the same signal would make it more differentiable".

During the design phase, four participants increased the number of pulses and the inter-pulse interval duration to optimise the perception of the tacton in turbulent situation. 11 participants saw the

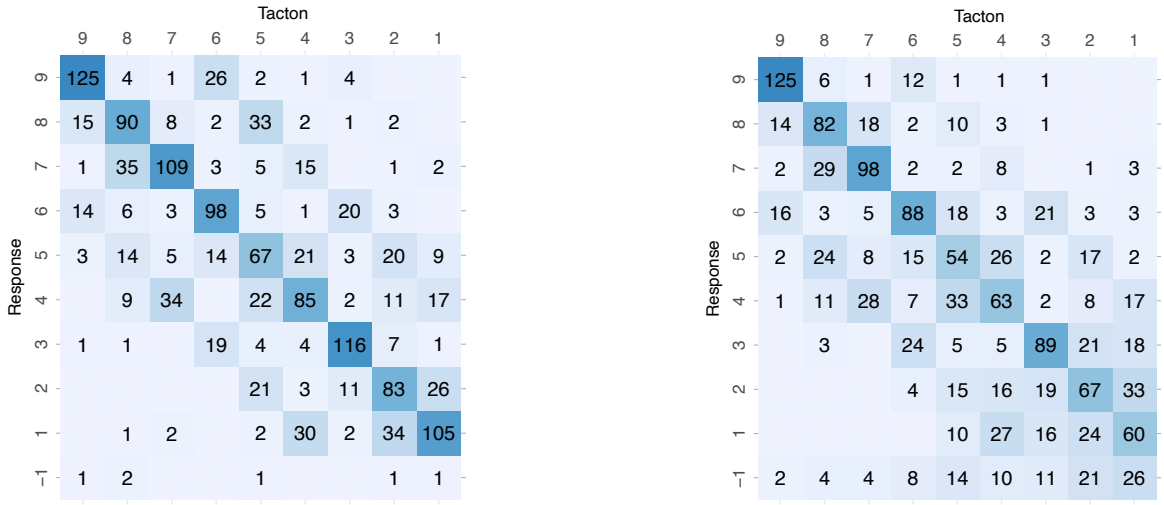

Figure 8: Confusion matrices for tacton identification in *NT* (left) and *VUT* (right). -1 denotes an absence of response.

tacton duration as the most resilient characteristic to turbulence, and in particular the number of pulses for some of them. Combining strong amplitude and high frequency was also seen as resilient to turbulence by the participants.

All participants envisaged tactons T7, T8 and T9, all three vibrating at 210Hz, as "very urgent" alarms. However, there was no consensus on which tactons could constitute "moderately urgent" and "non-urgent" alarms. No tacton with *fast* rhythm was associated to any alarm. One of the participants commented: "in turbulence, the tactons T1, T4 and T7 look like a single long vibration". Finally, as an open comment, a participant with a piloting license underlined the difficulty "to associate a type of alert with a type of vibration, in a context where the pilot's attention is already divided between several other senses (hearing/seeing)", even if the vibration can be a good way "to notify the pilot or to attract his attention".

5 DISCUSSION

5.1 Effect on vibrotactile pattern identification

The first part of our study aimed at establishing an effect of turbulence on vibrotactile pattern identification (Q1). In all locations (hand, thigh and wrist), the identification rates significantly decreased as the level of turbulence increased. Turbulence had therefore a detrimental effect on the tacton identification performance, which validates H1. Our results with respect to the effect of ambient motion on tactile feedback are in line with the findings in the mobile interaction and the automotive domain [21, 22].

The tacton identification took longer on the *thigh* and on the *wrist* as the turbulence increased, which confirms H1. Surprisingly, we could not find similar results on the *hand* as we found *VUT* to be faster than *NT*. The task was harder for participants, as shown by the lowest identification success rate of the *hand* across all locations in *NT*. It may have been due to the fact that the measured RMS vibration acceleration was much lower on the flight stick than on the other output devices since the actuator was located inside the device case as reported in section 3.1. That being said, it is worth mentioning that *thigh* had the biggest performance drop under turbulence making it a poor candidate for tactile feedback in the cockpit. This might be explained by the fact that the thigh was closely connected to the motion platform structure, while the arms of participants could move freely.

The information transfer value decreased as the turbulence level increased, which also corroborates H1. The average information transfer value across all locations significantly decreased by 0.2 bits from *NT* to *VUT*. Participants were able to identify 4.9, 4.5 and 4.29 out of the 9 tactons in *NT*, *UT* and *VUT*, respectively. This indicates that participants may not be able to discern more than 4 different tactons in turbulence. As before, the information transfer average value across turbulence levels was the lowest for the *hand*. This is surprising as the hand is known to be more sensitive than the wrist or the thigh to tactile stimulation [12].

5.2 Vibrotactile pattern design for turbulence

The second part of the study aimed at identifying vibrotactile pattern characteristics that may be resilient to turbulence (Q2). First, it is worth mentioning that the simulated turbulence based on the ISO 2631-1 standard and previous studies [8, 11, 25] was representative of real turbulence. This was confirmed by most of our participants including licensed pilots.

In *NT* and *VUT*, low confusion was found between *low* and *high* frequencies regardless of the *rhythm*. This result is in line with previous findings in the automotive domain which found a low discernibility between 80 and 140 Hz, and 140 and 220 Hz tactons [21]. In our study, the difference between the low and high frequencies was 180 Hz. This can be used as a safe distance to avoid tactons' frequency confusion under turbulence. During the design phase, most participants set the tacton frequency above 210 Hz across all devices, which seems to be a reasonable minimum frequency for designing tactons that can be comfortably perceivable during turbulence.

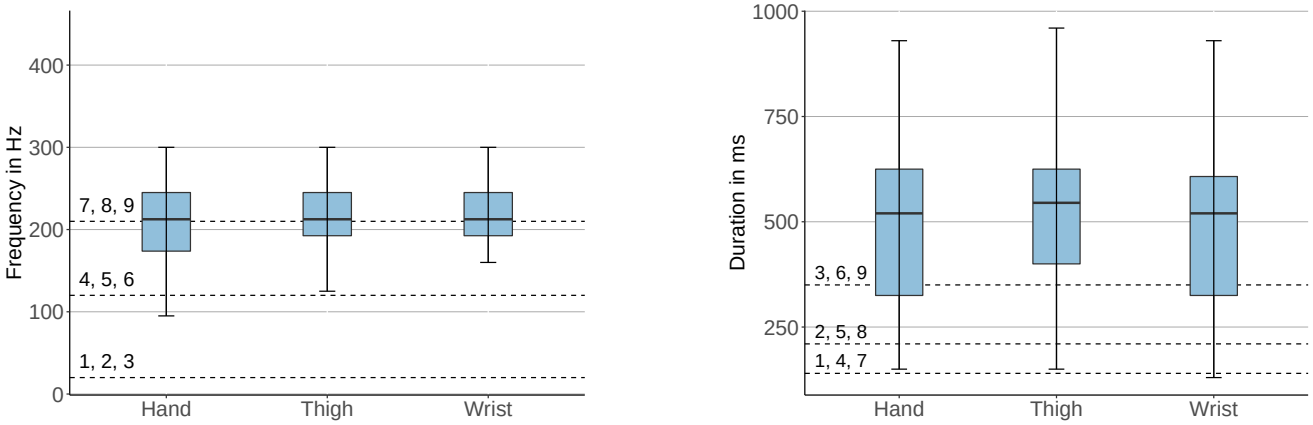

Figure 9: Participants' design median frequency (left) and median vibration time (right) settings by device. Dashed lines represent the tactons' parameters values used in the study.

Moving from *NT* to *VUT*, we found that absences of response grew considerably especially for tacons with *low* frequency. This reveals that participants could not detect all tactons under turbulence. We also found that turbulence caused confusion about rhythm, which invalidates H4. This contradicts previous research which reports that rhythm is more efficient in encoding information than signal modulation in tactons [6, 7, 48]. Rhythm carries a significant amount of information that facilitates tactons identification [9, 57]. This result shows how vibrotactile feedback expressiveness is substantially diminished under turbulence.

We also found the tactons with the *slow* rhythm to be less error-prone than the others within a same frequency. This supports findings in prior research which highlight the importance of inter-pulse intervals and the difficulty to perceive rhythm in the low frequencies [3, 9]. In the design phase, participants reduced the number of pulses and increased the pulse and inter-pulse interval durations of our initial *slow* setting. Even though tactons T3, T6 and T9 were among the most identifiable tactons under turbulence in our study, it seems that our setting (5 pulses of 350 ms with 187 ms IPI) was not salient enough. For participants, a tacton made of long and slow pulses was more resilient to turbulence. It is worth noting that the tacton rhythm was closely linked to duration in our design. Increasing the pulse and inter-pulse interval durations will increase the pattern total duration, which may not be desirable in some situations.

5.3 Limitations and perspectives

Our research is a first attempt to identify design considerations for building vibrotactile feedback that can be resilient to turbulence. Although the outcomes of our study can support the design of tactons that are resilient to turbulence, further research is needed to increase their expressiveness and their resilience to environmental vibrations.

Our findings show that frequency, pulse and inter-pulse interval durations are essential characteristics to make tactons more resilient to turbulence. The tactons in the study were designed to explore a broad vibrotactile perceptual space like in [2, 3]. While our results can support practitioners to design vibrotactile feedback for anyone experiencing turbulence in aircraft including pilots, a more precise study could identify the just noticeable frequency difference under turbulence.

Even in very uncomfortable turbulence, participants were able to identify distinctive tactons. Our focus was to identify the characteristics that allowed participants to identify the tactons under turbulence. Thus, visual depictions were provided during the task to minimise confounding associated to the memorisation of tactons as recalls might have had randomly affected the participants' performance. As a matter of fact, psychologists are still trying to understand the functioning of vibrotactile working memory [54].

Even though the same affordable and common actuators were used in all conditions of our study, the vibration acceleration was lower at the surface of the flight stick as reported in section 3.1. Spring-centered joysticks, such as the flight stick used in our study, exerts some restraining force, which opposes to any force applied to the device [24]. This may have dampened the vibrations sent to the participants. In addition, pressure has a detrimental effect on vibrotactile sensitity especially at low force [5, 33]. Since the participant were holding the flight stick with their hand during our experiment, it may have altered the stimuli perception even more. Therefore, designers should consider such criteria when integrating vibrotactile output into input devices that use spring force for actuation.

The participants' defined tactons characteristics have confirmed the performance data. Since no piloting skill or experience was required to perform the task in our study, our participants were diverse. Therefore, we cannot guarantee that these tactons will be suitable for pilots. We plan to conduct additional research with expert pilots to design intelligible and identifiable tactons, which will be evaluated in ecological settings.

5.4 Tactilients: Tactons resilient to turbulence

Our research has shown that turbulence degrade the performance of vibrotactile pattern identification and reduce vibrotactile pattern expressiveness. Turbulence cause whole-body vibration which can

cause temporal and frequency masking [42, 43]. Nevertheless, some tactons were still locally identifiable on the body even under very uncomfortable turbulence. In particular, vibrotactile patterns with high frequency, long pulse and inter-pulse interval durations were the most identifiable. We call such robust patterns *tactillients*.

Whole-body vibration occur when vibration from a shaking surface remotely affect body parts of a human [29]. They may come from motion on uneven surfaces in transports, from mechanical machinery in industrial settings or even from loud music in concerts [29, 43]. The simulated levels of turbulence in our study were designed according to ISO 2631-1, which reports level of comfort reactions to vibration environments in public transports. It is worth noting that our findings are conformed with the ones in the mobile interaction and the automotive domain [21, 22]. Therefore, the results reported in this article may be applicable to other forms of transportation where the passengers are subjected to vibration. That being said, further research is necessary to transpose our findings to other contexts. We hope that our research will support the investigation and the design of *tactilients*, tactons that can be more resilient to whole-body and environmental vibration.

5.5 Implication for design

To support researchers and practitionners, we propose a list of considerations for the design of *tactilients* based on the several findings that emerged from our study:

(1) Prefer body locations that are not directly connected to the turbulence. In our study, we found the biggest performance drop on *thigh*, which was moving with the motion platform structure.
(2) Limit the number of vibrotactile patterns when designing for turbulence. The participants' performance and the information transfer decreased under turbulence for all body locations, resulting in the average identification of only 4 over 9 tactons in our study.
(3) Prefer high frequency tactons. In our study, most of participants set the tacton frequency above 200 Hz for any of the *location* in turbulence. The average frequency across *wrist* and *thigh* was 211 Hz, which translates into an RMS acceleration of 1.25 Grms on our actuators.
(4) Provide enough distance between frequencies. Our results showed low confusion between tactons with *low* and *high* frequencies under turbulence. The distance between the two levels was 180 Hz which translates into an RMS acceleration of 0.75 Grms on our actuators.
(5) Prefer tactons which are long and slow. Participants increased pulse and inter-pulse intervals of our longest tacton (pulse = 350 ms, IPI = 187 ms) to optimise the tacton identification under turbulence. An average of 2.8 s divided into 4 pulses of 492 ms and 280 ms IPI was found across participants' designs.

6 CONCLUSION

Researchers have proposed promising vibrotactile feedback designs for preventing the overload of pilots' visual and auditory channels. Although most of the research have been evaluated in a static environment, aircraft are subjected to vibrations and turbulence that can affect tactile perception. In this paper, we investigated the effect of turbulence on vibrotactile pattern identification. Our study with simulated turbulence shows that *tactilients*, long and slow tactons with high frequencies delivered on a body part that is not directly connected to turbulence, are the most resilient to turbulence. Based on our findings, we provide a list of considerations to support practitioners for designing *tactilients*, vibrotactile patterns that are more resilient to turbulence. In future work, we plan to validate our experimental results with licensed pilots in simulated and real flying tasks where their attention may be limited, and to design *tactilients* that can deliver meaningful information to support pilots. We hope that our research will lay the cornerstone for designing *tactilients*.

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