
# Effects of external perturbations on tactile perception by electrovibration

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**Abstract**—Navigating touchscreens in vehicles becomes increasingly challenging when subjected to external perturbations like air turbulence or bumpy roads. These perturbations can lead to a loss in task performance, reduced finger accuracy, and increased frustration among users. To address these issues, electrovibration has emerged as a promising technology to enhance touchscreen interactions by providing users with better feedback and maintaining touch stability even under challenging conditions. Before we investigate if electrovibration helps users in challenging conditions, first the effects of external perturbations on tactile perception by electrovibration must be found. To investigate the impact of external perturbations on electrovibration perception, we conducted psychophysical experiments with 18 participants interacting with an electrostatic display mounted on the cockpit of the SIMONA flight simulator. We measured participants' absolute detection thresholds for electrovibration pulses generated using 100 Hz input voltage for durations of 0.2 and 0.5 seconds, simulating a ridge and a button or slider. The measurements were taken under no-turbulence conditions and two different turbulence conditions. Our results revealed that turbulence significantly affects vertical finger movement, average normal force, and the change in force applied to the screen by participants. This combination of factors, along with the 0.2-second pulse duration, makes electrovibration more difficult to perceive or even imperceptible. The 0.5-second electrovibration pulse was perceived better overall and remained unaffected by turbulence. This highlights the strong significance of pulse duration on the absolute threshold of electrovibration. Therefore, to counteract the negative effects of perturbations on perception, electrovibration should be employed for longer durations when perturbations are present.

**Index Terms**—Electrovibration, turbulence, tactile perception, psychophysical experiments, touch screen, simulation

## 1 Introduction

A world without touchscreens is unimaginable today; they have been used in many electronic devices such as smartphones, tablet computers, laptops, kiosks, and digital information panels. Moreover, touchscreens are becoming more prevalent in vehicle cockpits, like in cars, planes, and ships. According to S&P Global Mobility, in 2022, 78.6% of cars were equipped with a center stack display, of which 93.5% were touchscreens [1]. In 2019, Airbus started to deliver their A350 XWB models with three touchscreens in the cockpit to be used by the pilot [2].

Touchscreens offer multiple advantages over conventional buttons and knobs in vehicle cockpits [3]. They provide design flexibility by combining display, input, and feedback functionalities in one module. Large quantities of information can be incorporated by touchscreens while being easily updatable by reconfiguring the graphical user interfaces (GUIs) instead of having to rewire mechanical controls. Finally, touchscreens promote intuitive interactions by pointing gestures. These advantages show us why touchscreens are so popular in vehicle cockpits today.

However, some problems also emerge when using touchscreen in vehicle cockpits. One of the problems that emerge is that touchscreens provide no tactile- or aural feedback. Traditional knobs and buttons provide feedback through force, sound, and other manners [4]. The lack of these types of feedback means the user has to confirm his or her action by using other methods, like visually checking if a button is pressed. This can lead to dangerous situations in traffic for example, when the user's eyes are on the touchscreen instead of being on the road.

Moreover, it is found to be difficult to use a touchscreen during external perturbations, such as turbulence in an aircraft, a bumpy road in a car, or waves in a ship. These perturbations cause the user and the screen to vibrate, which causes difficulty in using the touchscreen [5], [6]. Various researchers showed that vibrations in the environment negatively affect people trying to accomplish tasks with various input devices. McLeod et al. show how joystick input while performing tasks was negatively affected by ship motion [7]. Similar effects were found in military vehicles and trains [8], [9]. These effects are also found when considering touchscreens in vehicle cockpits. The effects of external perturbations on a touchscreen user have been investigated more extensively since the technology is gaining popularity. This research is mainly done in various simulators, where simulated turbulence or other external perturbations are presented to disturb the user while touching the touchscreen. Research shows that user performance deteriorates when turbulence is encountered. This starts to show in increased task completion time, an increase in errors made, and a higher workload for the user [5], [6], [10]. Cockburn et al. found a doubling in selection time during a target selection task, changing from 1163 ms during no turbulence conditions to 2360 ms during high turbulence conditions [5]. Several sources found that bigger buttons and more spacing between buttons improve the user performance during turbulence, but do not eliminate the negative effects

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turbulence has on the task performance of the user [6], [10]. Other methods to improve user performance have been investigated as well, like giving visual and auditory feedback [11]. This did, however, not improve performance significantly and this research showed how task completion time increased by 38-70% with 4-5 times more errors during turbulence, confirming the findings done by Dodd et al. [6]. Next to this research, a stencil overlay, trackball, or grips on the side of the screen do not improve performance either [5], [12]. The negative effects of external perturbations on user performance are explained by Khoshnewiszadeh and Pool as biodynamic feedthrough (BDFT) [13]. BDFT is the effect of involuntary limb movement due to vibrations in the environment, which is present during external perturbations in vehicle cockpits. Khoshnewiszadeh and Pool investigate if BDFT cancellation by modeling is a way to eliminate the problems encountered by the users. The BDFT is canceled by 63% in one of their tasks, but only 12% in another. This seems to suggest that this method is not task-to-task generalizable.

So far, none of the methods that are investigated provide a complete solution to the problems that emerge when using touchscreens in cockpits. Instead of using these methods, a form of surface haptics could be used. Surface haptics are the haptic effects on physical surfaces such as touchscreens, which could improve task performance during external perturbations. During this research, electrovibration, a form of surface haptics is investigated as a solution to the decrease in task performance during external perturbations.

Electrovibration is described as modulating the perceived friction due to the induced electrostatic force between a finger and a high-voltage supplied plate [14]. This phenomenon was first discovered in 1953 by Mallinckrodt [15], after which it has been investigated extensively over the last few decades. It was found that an alternating current through a conductive material creates an attractive electrostatic force on the finger. The conductive fluids in the finger and the conductive layer in a screen are separated by an insulating layer and the stratum corneum, the outer layer of the finger. The electrostatic force creates an effect of increased friction felt by the user when the finger is moving across the screen. Electrovibration is sensed mostly by the Pacinian corpuscles [16]. These mechanoreceptors are located in human fingers and give us a sense of vibrations with frequencies around a few hundred Hertz [17]. Vardar and Kuchenbecker investigated the effect of finger motion on the perception of electrovibration. They found that with a stationary finger, electrovibration is hardly perceivable and with one moving finger, the perception is strongest [18]. This is explained as being a result of the lateral part of the electrostatic force, which is not present when the finger is stationary. For a stationary finger, the electrostatic force exists only in the normal direction of the finger, which is too subtle to be perceived. Researchers found that using electrovibration during pan gestures or dragging tasks on touchscreens improves user performance [19], [20]. Their findings show that users' accuracy and efficiency increase, resulting in smaller errors made and quicker task completion times. These effects are explained as a result of the fact that the higher friction makes it easier to navigate your finger to the desired location without overshooting due to a slippery screen. Their results therefore show that electrovibration positively affects the task performance of a touchscreen user. Next, electrovibration could be used in button or ridge rendering on the touchscreen. This way, a button or slider on the touchscreen could provide electrovibration haptic feedback, which could help the user stay on the button or slider while using it. This would improve task performance as well.

External mechanical perturbations in vehicle cockpits likely influence the perception of electrovibration. This could be in the form of tactile masking. Tactile masking could be described as: "Two stimuli activating a sensory system simultaneously or in rapid succession can produce a variety of perceptual experiences. The most common and widely studied is masking, in which one stimulus decreases the detectability of another." This is the description of tactile masking given by Verrillo et al. [21]. In the case of external perturbations and electrovibration, the tactile masker would be the external perturbations, with the electrovibration stimulus being masked. Researchers found that the effect of tactile masking is still present whenever the masker and the masked stimulus are in different locations. However, the masking effect decreases in comparison to when the stimuli are both at the same location [21], [22], [23]. It was however found by Morioka and Griffin that masking does also occur with a vibrating chair [24], which could indicate a vibrating environment could also mask the perception of a touchscreen user. However, it was also found in their research and by many others that tactile masking is strongest whenever the frequencies of both stimuli are approximately equal [21], [22], [24], [25], [26]. This is not the case with the combination of external perturbations like turbulence and electrovibration since turbulence has a frequency typically lower than 5 Hz [10], [13], and electrovibration is felt strongest at frequencies around 200 Hz [26], [27]. Therefore it seems unlikely that tactile masking will appear in the case of turbulence and electrovibration. Instead, turbulence could influence the perception of electrovibration by interfering physically with the touchscreen user's finger. This could occur due to the changes in the contact area of the finger and the screen, the distance from the finger to the screen, and the changes in exploration velocity, all due to the BDFT caused by turbulence. The electrostatic force induced by the electrovibration screen is proportional to these three variables and therefore, the perception of electrovibration would change with the change of these variables [28].

### 1.1 Hypotheses

There has not yet been any research on the combination of external perturbations and electrovibration. To have a better view of this combination and see if electrovibration could be a feasible option to counteract the negative effects of external perturbations, the goal of this research is to see what the effects of external perturbations are on the perception of electrovibration. Therefore, the research question that is answered during this research is: What is the effect of external vehicle perturbations on tactile perception by electrovibration? To answer this question, we designed a psychophysical experiment that takes into account 2 different durations of electrovibration and 3 different types of turbulence.

Before designing the experiment, hypotheses about the research have been made. First of all, it is expected that a shorter electrovibration pulse will be more difficult to be felt, which will result in higher thresholds for electrovibration with short pulse duration. Next, it is expected that the external perturbations negatively affect the perception of electrovibration, which will result in higher thresholds. Moreover, it is expected that because of the involuntary limb movement due to the vertical perturbations, the vertical finger speed, the force applied on the screen by the participants, and the change in force per second will all significantly increase during the experiments.

## 2 Materials and methods

To investigate the effects of external perturbations on the perception of electrovibration, we conducted psychophysical experiments to determine the absolute perceptual threshold of electrovibration.

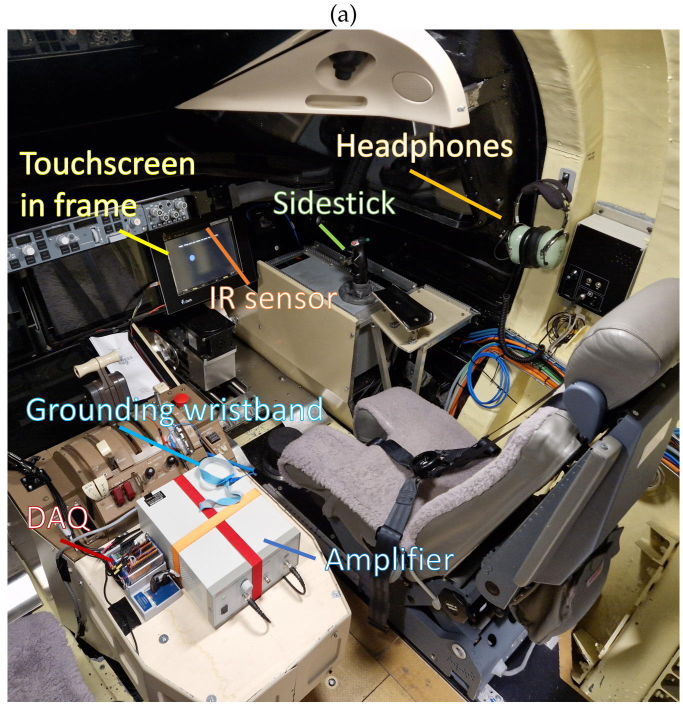
### 2.1 Participants

The psychophysical experiments were conducted on 18 participants (14 male, 4 female) in the SIMONA Research Simulator, shown in figure 1a. All participants were right-handed. The average age was 25.2 (SD: 4.1). Most participants were students of the Delft University of Technology. Before every experiment, the touchscreen was cleaned with alcohol. Participants were asked to clean their hands before the experiment. All participants read and signed the informed consent form before participating in the experiment. The ethical committee of the Delft University of Technology approved the experiment, with case number 3280. All participants watched the safety video for the SIMONA Research Simulator before the experiment.

### 2.2 Apparatus

The experimental setup inside the SIMONA Research Simulator is visible in figure 1b. During the experiment, the participant sat strapped in by the five-point harness in the right seat of the SIMONA Research Simulator. The researcher instructed the participants from the simulator control room using a microphone and headphones. In front of the participant, a touchscreen was mounted with an 18-degree angle to fully vertical in a custom-made frame fitted on top of the primary flight display. The frame encapsulated the edges of the touchscreen, the sensors, and the wiring to keep the setup in place while the simulator was moving and as a safety measure for the participants. The touchscreen (SCT3250, 3M Inc.) was mounted on four force sensors (FSG020WNPB, Honeywell Inc.), attached to the frame on the corners of the touchscreen. These sensors measure the normal force exerted on the touchscreen by the user's finger. The forces were sampled by a data acquisition board (NI-9205, NI Inc.) at a rate of 2 kHz. An infrared position sensor (NNAMC2300PCEV, Neonode Inc.) was used to determine the participant's finger position and velocity. The voltage signal applied to the touchscreen was generated by a data acquisition card (NI-9264, NI Inc.) and then augmented by a high-voltage amplifier (HVA200, Thorlabs Inc.). The infrared position sensor and the data acquisition card were connected via USB cable extenders to a computer in the control room of the SIMONA Research Simulator. The participants wore an anti-static wristband on their non-dominant wrist for grounding, and they wore pilot headphones with which they could communicate and hear instructions coming from the control room. During the experiment, the participants listened to aircraft engine noise


(a)




(b)

Fig. 1: (a) The SIMONA Research Simulator of the Delft University of Technology. (b) Experimental setup inside the cabin of the SIMONA Research Simulator. The seat is pushed back from its experimental position.

to mask any auditory clues from the simulators' motion system. The participant's input was recorded via buttons on a sidestick available in the simulator cabin. This sidestick was on the right side of the seat, which meant all participants had to use the same hand to press the buttons and touch the screen. A delay of at least one second was used between pressing the button and starting the trial to not lose touching data.

The SIMONA Research Simulator (SRS) at the Faculty of Aerospace Engineering of the Delft University of Technology was used to simulate the external perturbations in the form of turbulence. The SRS is shown in figure 1a and has a six-degrees-of-freedom hexapod motion system with a maximum stroke of 1.25 meters and a capability to generate up to 1.5 g heave (vertical) accelerations. In figure 1b, the right seat in the simulator is pushed back. During experiments, the participants were able to move the seat to the front to be in a comfortable position when touching the screen.

## 2.3 Stimuli

### 2.3.1 Visuals

During the experiment, the participants had to touch the screen with the index finger of their dominant hand. The participant moved their finger at a speed of 50 mm/s, following a moving cursor on the LCD screen. They moved one stroke of two seconds to the right, with the stimulus with a varying duration in the middle, and one stroke of two seconds to the left with the stimulus in the middle. Having a speed of 50 mm/s means the exploration area is 100 mm wide. An animation shows the exploration in figure 2. The green ball depicts the cursor the participants had to follow. The 0.5-second electrovibration stimulus is visualized in the middle of the exploration area.

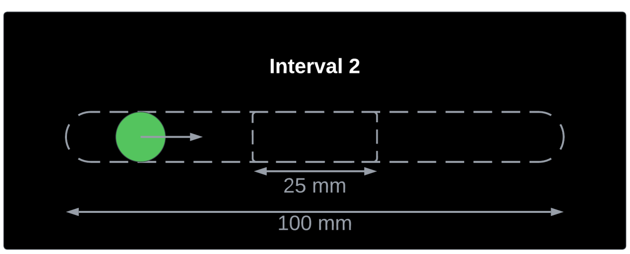



Fig. 2: Visuals during the second interval, showing a green ball and "interval 2" on the screen. The gray and dashed lines were not visible to the participant. The size of the 0.5-second interval is shown by the dashed lines.

### 2.3.2 Haptic stimuli

During the experiment, an electrovibration stimulus was present for either 0.2 or 0.5 seconds twice in 4 seconds. The 0.2-second duration is used to render an edge or a small button on the touchscreen. The longer 0.5-second duration simulates a bigger button or a small slider. A schematic view of one trial of the experiment with a 0.5-second electrovibration stimulus is shown in figure 3. The electrovibration stimulus is an alternating voltage, with a sinusoidal shape and a frequency of 100 Hz. Using a sinusoidal electrovibration stimulus causes frequency doubling for the electrostatic force. This is due to the electrostatic force being proportional to the input voltage squared, described in equation (1) [28]. In this equation, $U$ denotes the input voltage, $A$ denotes the contact area of the finger and the screen, and $\epsilon_0$ denotes the permittivity of a vacuum. $d^{sc}$, $d^a$, and $d^i$ denote the thickness of the Stratum Corneum, the outer layer of the finger, the thickness of the airgap between the finger and the screen, and the thickness of the insulator layer in the screen. $\epsilon^{sc}$, $\epsilon^a$, and $\epsilon^i$ denote the permittivity of these layers. When the input voltage is sinusoidal, the frequency of the electrostatic force is twice the frequency of the input voltage. For this reason, half of the desired electrostatic force frequency is used for the sinusoidal input voltage. The vibration frequency felt by the participants is 200 Hz in this case. This frequency is chosen because it is in the range of frequencies at which electrovibration is best perceived [26], [27]. The amplitude of the electrovibration stimulus changes throughout the staircase method, which is explained in section 2.4, and starts with an initial amplitude of 50 V. This amplitude was chosen by doing preliminary research and training sessions with participants. It was found that all participants were easily able to feel the stimulus.

$$F_e = \frac{\epsilon_0 A U^2}{2(\frac{d^{sc}}{\epsilon^{sc}} + \frac{d^a}{\epsilon^a} + \frac{d^i}{\epsilon^i})(d^{sc} + d^a + d^i)} \tag{1}$$

### 2.3.3 Turbulence stimuli

To simulate the turbulence, two different stimuli are used: a Gaussian distribution of frequencies and a combination of sinusoidals. These forms of turbulence were used to make the turbulence unpredictable for the participants. Both turbulence signals were designed and used in earlier research [29]. The multisine turbulence signal was designed by using the following equation.

$$\sum_{k=1}^{10} A_k sin(\omega_k t + \phi_k) \tag{2}$$

Ten sinusoids were cumulatively summed up to create the multisine signal. In equation 2, $A_k$ is the amplitude of the sinusoid, $\omega_k$ is the frequency of the sinusoid and $\phi_k$ is the phase offset of the sinusoid. The acceleration amplitudes of the sinusoids ranged from 0.016 $m/s^2$ to 0.73 $m/s^2$ with frequencies of the sinusoids ranging from 0.1 Hz to 3 Hz. These components were selected to cover as much of the frequencies humans are sensible to, without becoming recognizable for the participants. The Gaussian turbulence signal is generated by using a Gaussian distributed probability density function of the components of the turbulence velocity field. This signal was filtered with a second-order low-pass filter with a cut-off frequency of 10 Hz, because of limitations of the model used and because of the physical limitations of the simulator, which would be damaged when exposed to high-frequency motion. The Gaussian turbulence is a more realistic depiction of air turbulence, compared to a less realistic, but more intense multisine turbulence. Both the original turbulence signals, the Gaussian and the multisine, had a duration of 90 seconds. For the experiment, signals with a duration of six seconds were used. The extra two seconds were needed for the fade-in and fade-out of one second of the turbulence signal. The fade-in and fade-out are used to go from a stationary condition to a representative turbulence condition and vice versa. Going from a stationary condition to full turbulence at once would create an uncomfortably large acceleration. During one trial of the experiment, the same turbulence stimulus was used for both intervals of the trial, shown in figure 3, to enable an unbiased comparison between the two intervals. For different trials, different turbulence signals were used. Ten different signals with a duration of six seconds were chosen from both the original 90-second signals. The turbulence per trial was a randomized choice from these ten signals.

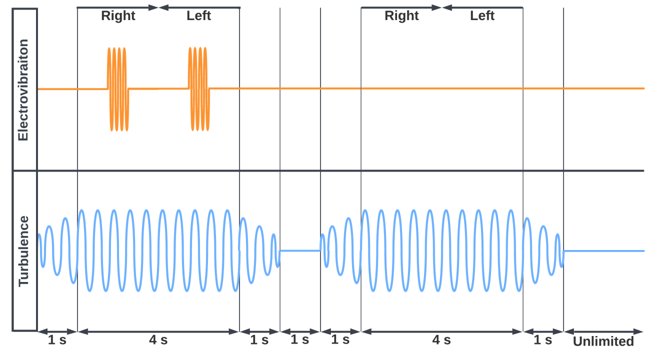



Fig. 3: A schematic representation of one trial of the experiment. In the turbulence signal, the one-second fade-in and fade-out are visible for every interval. The finger movement direction is shown at the top. During this trial, the electrovibration pulses are in the first interval. These pulses have a duration of 0.5 seconds.

## 2.4 Procedure

After making sure the participants' hands were washed, the screen was cleaned with alcohol, and they were briefed about safety and potential motion sickness. Then, the participants were instructed to take a seat in the SIMONA Research Simulator. The experiment uses an adaptive staircase with a three-down/one-up method to determine the absolute threshold of electrovibration. This method needs three correct answers to go down in voltage and one wrong answer to go up. This staircase was used by comparing two intervals of four seconds during one trial, one containing an electrovibration stimulus and the other without such a stimulus. After experiencing the two intervals, the participants can indicate which interval contained the stimulus according to them, for which they have unlimited time, after which they can start the next trial. Indicating the trial and starting the next trial is done by using the buttons on the sidestick, visible in figure 1b. A red button had to be pressed for interval 1, and a green button for interval 2. The trigger button on the front of the sidestick had to be pressed to continue to the next trial. Only the first answer by a button press is documented. In figure 3, an example trial is shown. This entire sequence seen in the figure is started by pressing the trigger button on the sidestick once. The final section on the right is the time to choose the interval and continue to the next trial. The time allocated for these actions is unlimited.

In figure 4 an example staircase for the experiment is presented. In this figure, the three-down/one-up method is visible. After three (consecutive) correct answers, the voltage applied to the electrovibration screen is lowered. The amplitude goes down first with steps of 5 dB until one wrong answer, after which the amplitude increases by 5 dB, and the step size is changed to 1 dB. A change from increasing intensity to decreasing and vice versa is called a reversal. After 5 reversals in a $\pm 1$ dB level, the mean value of these last 5 reversals is taken as the absolute threshold. The dB unit used in research on electrovibration is described as $20log_{10}(V_p)$ with $V_p$ being the peak voltage of the touchscreen.

Six staircases were conducted with three different modes of turbulence and two different electrovibration pulse lengths. There were six different orders of conditions, such that every condition was in every position in the order. This meant that for three orders, the participants started with the 0.2-second electrovibration stimulus, whereas for the other three orders, they started with the 0.5-second electrovibration stimulus. 18 participants took part in the experiment to have a uniform distribution of orders of conditions. After researching these six conditions, the effects of different turbulence forms on different electrovibration stimuli could be determined.

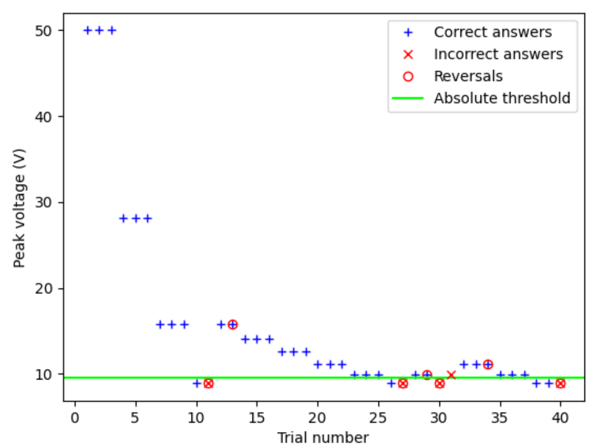



Fig. 4: An example staircase plot showing the three-down/one-up staircase method. The step size was 5 dB until the first reversal, after which it was changed to 1 dB. The final threshold was calculated as the average of the last five reversals in a $\pm 1$ dB range.

## 2.5 Data analysis

All data acquired from the experiment was stored in one file per staircase and was analyzed with a Matlab program. The force and finger position data consisted of a time series per staircase, with parts of the breaks present. From these time series, the trial data was extracted by taking only the data from the start and finish of every interval. This means any data from either the breaks between trials or the break between intervals was omitted. The force data was recorded with 2000 Hz, this was found to be the maximum frequency at which the sensors were able to work as intended. The finger position data was recorded at 100 Hz, this is the locked frequency at which the sensor records. After calibrating the force sensors, a conversion from Volt to Newton was made and the clamping force of the frame was calculated. This was subtracted from every sensor's raw data, after which the average normal force was calculated by using the force from every sensor and the finger location to make a weighted average. The force data was then filtered by a zero-phase digital second-order low-pass Butterworth filter. This was done to reduce the effect of high-frequency noise, especially on the force change signal, which is the time derivative of the force signal. The force calibration and force calculations are described in appendix B.1. The finger location data was converted from pixel to mm, after which the data points outside of the screen were filtered out. Then the x- and y-location time series were differentiated, to obtain the finger speed in both directions. In this data, values higher than 1000 mm/s were filtered out. These higher values occurred as the location made a jump. Both finger speed and force change were collected per time tick and were converted to be presented per second.

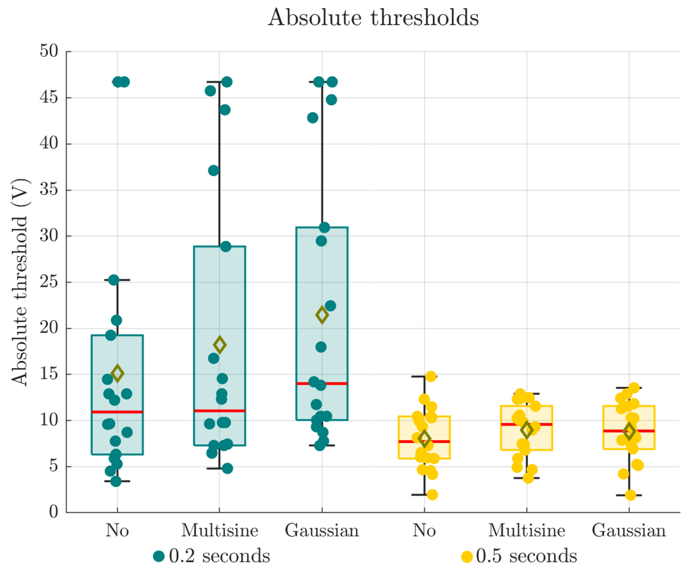



Fig. 5: Boxplots of the absolute thresholds of electrovibration. In green on the left are the three 0.2-second electrovibration conditions. In yellow on the right are the three 0.5-second electrovibration conditions. The dots indicate the individual data points, the red line indicates the median and the diamond indicates the mean value.

## 3 Results

### 3.1 Thresholds

To observe the effect of turbulence on the perception of electrovibration, the absolute threshold of the electrovibration is measured. The thresholds are the main result of the staircase experiments. In figure 5 boxplots of the absolute thresholds of the perception of electrovibration are shown for the different conditions. After applying a Shapiro-Wilk test to this data, it is found that all the 0.2-second conditions are not normally distributed, whereas the 0.5-second conditions are all normally distributed. Therefore, we analyzed the threshold data using generalized linear mixed models (GLMM) with gamma distributions with the main effects of turbulence and duration of the electrovibration stimulus and random effect of participants. The models showed that there was no significant effect of turbulence on the absolute threshold ($p>0.05$). The electrovibration pulse duration had a significant effect, however ($p<0.001$). Also, the intercept, thus the interaction of the two effects, was significant ($p<0.001$) as well. Finally, the effect participants had on the data was also significant ($p<0.05$). After pairwise comparisons with Bonferonni corrections between the conditions, no significant effects were found. Notably is the difference in data spread between the two pulse length conditions. The mean standard deviation of the 0.2-second condition data is 14.25 whereas the mean standard deviation of the 0.5-second condition data is 3.95. These results show that the 0.5-second electrovibration pulse is much easier to be felt by touchscreen users during turbulence.

### 3.2 Finger speed

Next to the participants' choices, their finger location and speed were recorded. These variables were measured to see the physical effects of turbulence on the finger. The effect of turbulence on finger movement is visualized in figure 6. In figure 6a, the finger position during an experiment with no turbulence and 0.5 seconds of electrovibration is visible. In figure 6b, the finger position during an experiment with multisine turbulence and 0.5 seconds of electrovibration is visible. The effect of biodynamic feedthrough (BDFT) is visible on the finger position, with a straight horizontal line during no turbulence and large vertical movements during the multisin turbulence. The plots are sized approximately as the screens are, which shows the participant trying to follow a line in the center of the screen, where the cursor was moving. The vertical finger movement was influenced significantly because the turbulence had only vertical motion. After analyzing the effects on the average horizontal finger speed with generalized mixed models, it was found that there was no significant effect for either turbulence or pulse duration.

The effect of larger vertical movement of the finger is also visible in the boxplots in figure 7. In this figure, the average vertical finger speed for all experiment trials is used to compare the vertical speeds at different conditions. After applying a Shapiro-Wilk test to this data, it is found that half of the data is not normally distributed. However, since the data is not skewed to higher values Generalized linear mixed models (GLMM) with a normal distribution were used to analyze this data, with again the main effects of turbulence and duration of the electrovibration stimulus and random effect of participants. It was found that turbulence significantly affects vertical finger speed ($p<0.001$), whereas the pulse duration does not. The intercept of both effects is significant as well ($p<0.001$). It is also found that participants have a significant effect on the results ($p<0.05$). Pairwise comparisons with Bonferroni correction show that

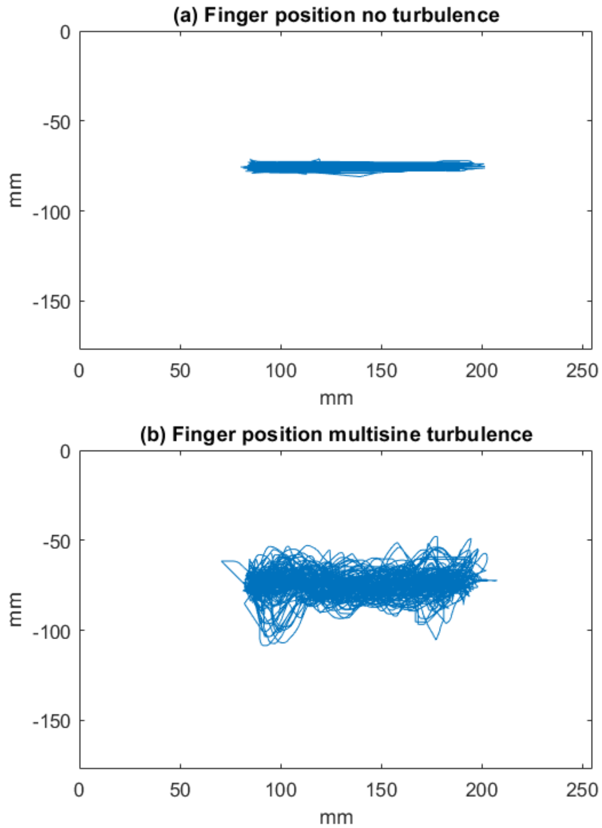



Fig. 6: (a) The finger position of a participant during a full experiment of 47 trials with no turbulence and 0.5 seconds electrovibration. (b) The finger position of a participant during an experiment of 34 trials with multisine turbulence and 0.5 seconds of electrovibration.

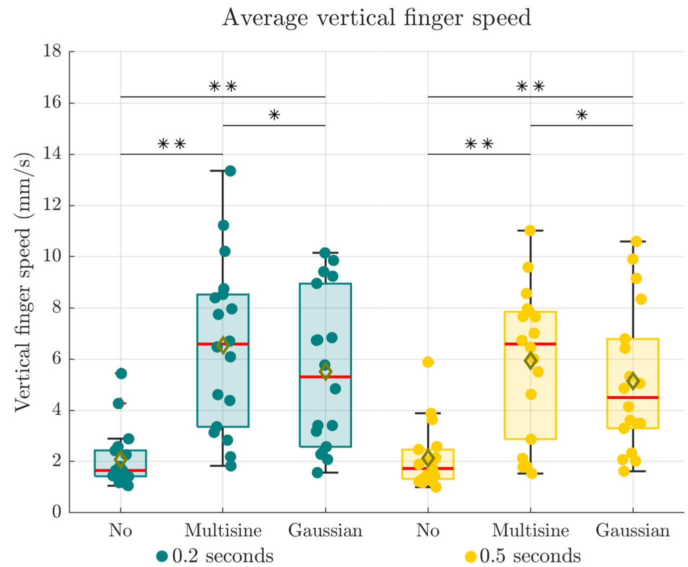



Fig. 7: Boxplots of the average vertical finger speed for the different conditions. A significant increase is visible when going from no turbulence to turbulence conditions. Boxes connected with a star (*) are significant pairs ($p<0.05$), and a double star (**) indicates ($p<0.001$).

there is a significant effect between no turbulence and both turbulence conditions ($p<0.001$), but also between the two different turbulence conditions ($p<0.05$). Note that the average vertical finger speed is higher during the multisine turbulence compared to the Gaussian turbulence. This can be explained by the amplitude of the multisine turbulence being higher than the amplitude of the Gaussian turbulence.

### 3.3 Normal force

Apart from the position data of the finger, the normal force exerted by the finger on the screen was also measured by four force sensors on the corners of the touchscreen. The normal force applied on an electrovibration screen is a vital measure since a higher normal force increases the touch surface and decreases the distance between the finger and the conductive layer in the screen and therefore increases the electrostatic force. In figure 8 the average normal force applied on the screen during the experiments is shown in boxplots. A Shapiro-Wilk test showed that only one of the conditions data is normally distributed. Since the data is also not skewed to higher values generalized linear mixed models with a normal distribution were used to analyze this data as well. Again, the main effects were turbulence

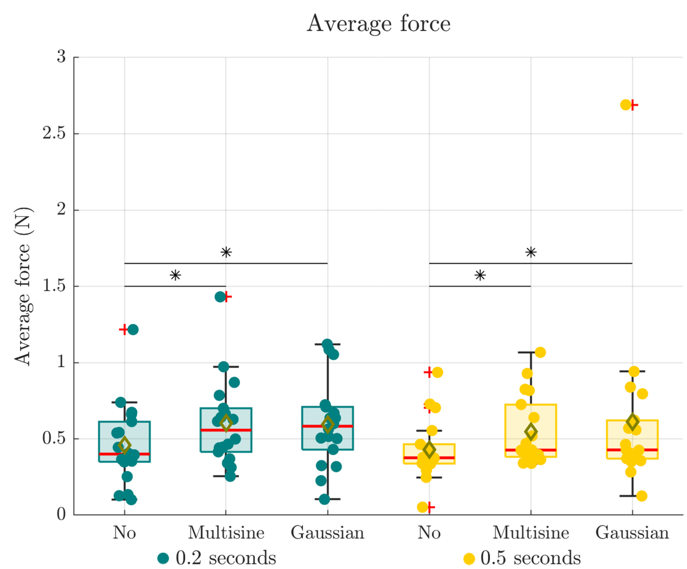



Fig. 8: Boxplots of the average force exerted on the screen during all trials of the experiments. Boxes connected with stars are significant pairs, * means ($p<0.05$), and ** indicates ($p<0.001$).

and electrovibration stimulus duration, and participants as the random effect. This resulted in a significant effect of turbulence on the average force ($p<0.05$), but not for the pulse duration. The intercept of these two effects is also strongly significant ($p<0.001$). It was also found that the participants had a significant effect on the data ($p<0.05$). When considering pairwise comparisons, the no turbulence condition is significantly different from both of the turbulence conditions ($p<0.05$). The increase in force during turbulence can be explained to be due to participants compensating for the BDFT by pressing harder on the screen, and the BDFT itself causing the participants to vary their force.

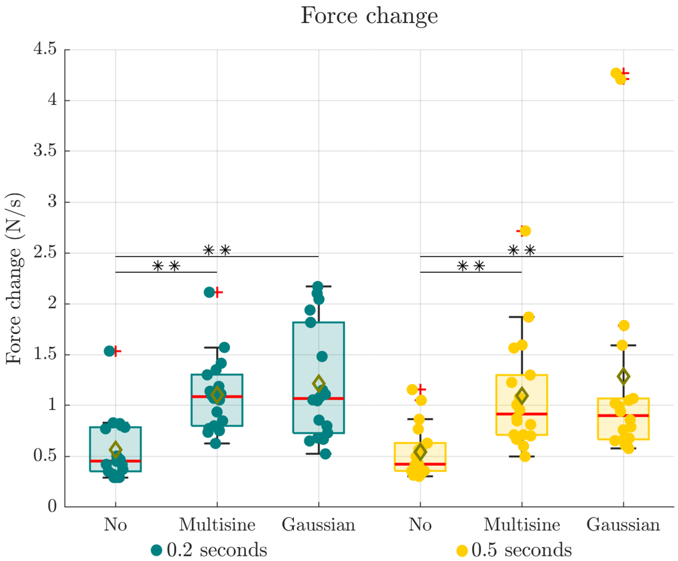



Fig. 9: Boxplots of the average absolute force change per second during all trials of the experiments. Boxes connected with stars are significant pairs, * indicates ($p<0.05$), and ** indicates ($p<0.001$).

By differentiating the force overtime after filtering out the high-frequency noise, the force change per second was calculated. Boxplots of the absolute force change are presented in figure 9. A Shapiro-Wilk test showed only one of the conditions had normally distributed data. Because of this, Generalized linear mixed models with a gamma distribution were used to analyze the effects of the different conditions on the average force change. Again, the main effects were turbulence and duration of the electrovibration stimulus, and the random effect was participants. The effect of turbulence on the average force change was found to be strongly significant ($p<0.001$). The effect of duration and the intercept of the turbulence and pulse duration were not significant. The effect of participants was significant as well ($p<0.05$). In figure 9, the results of the pairwise comparisons with Bonferroni correction are shown. The difference between the no turbulence condition and both of the turbulence conditions is strongly significant ($p<0.001$). The increase in force change during turbulence can be explained as the effect of BDFT, where involuntary movements in the touchscreen's normal direction change the force applied on the screen. The force change during Gaussian turbulence is higher, most likely because of the higher amount of small accelerations during this type of turbulence, compared to the lower amount of accelerations during multisine turbulence. The high change in force indicates participants have trouble keeping the force they intend to exert on the screen. High normal force changes during electrovibration could hamper the perceptional sensitivity of touchscreen users.

## 4 Discussion

In this research, the effects of turbulence and pulse duration on electrovibration were investigated. This was done by conducting psychophysical experiments on the absolute threshold of electrovibration. It was found that pulse duration significantly affects the perception of electrovibration. Next to this, it was found that turbulence has a significant effect on finger movement, the average normal force exerted on the screen, and the change in that force per second.

The hypotheses stated in section 1.1 are answered by the results acquired during the experiments. The first hypothesis stated that the shorter pulse duration would increase the absolute threshold. This hypothesis is accepted since a significant increase is found between the longer and the shorter pulse of electrovibration. The next hypothesis, stating that the turbulence would increase the absolute threshold, is rejected. No significant effect of the turbulence was found for the absolute thresholds. The effect of an increased threshold is only visible for the short duration of electrovibration and this is caused by the higher force change during turbulence, combined with erratic finger movement, which makes it harder to feel the short pulse of electrovibration. The short pulse time of 0.2 seconds is so short that a single acceleration of turbulence can cause the participant to miss the pulse, by lowering the normal force or moving the finger suddenly. During the longer pulse, that same acceleration is long enough to make a participant miss the pulse. As for the cause of the effect of an increased threshold, it was questioned if tactile masking would play a role in this experiment. From the results, it can be concluded that tactile masking is likely not the cause for the increase in threshold experienced under turbulence conditions. However, this is not yet proved by the results found in this research and is something to be investigated in the future.

After these hypotheses, it was hypothesized that the vertical finger speed would significantly increase during turbulence. This hypothesis is accepted since it was found that the average vertical finger speed does significantly increase during turbulence conditions. In the vertical finger speed results, it is found that the average vertical finger speed is higher during the multisine turbulence than during the Gaussian turbulence. This can be explained by the difference in amplitudes in the turbulence signals. The multisine signal has higher amplitudes, which causes higher vertical finger speeds. However, the Gaussian turbulence signal has smaller amplitudes as well. This results in lower vertical finger speeds, but because there are more small accelerations, it also produces higher normal force change. This is found in the results of the normal force change, visible in figure 9.

Finally, the last hypothesis stated that the turbulence would give a significant increase in the normal force exerted by the participants and the change in normal force. This hypothesis is accepted as well because it was found in the results that there was a significant increase in the normal force exerted by the participants, which was due to compensation for the BDFT. The higher normal force change is likely due to the BDFT, which changes the change rate of the force a touchscreen user exerts on the screen by making the arm and hand of the participant move involuntarily.

Next to the effects found in the results, several participants complained about their fingers jumping over the screen, which could make them miss the 0.2-second electrovibration pulse. The jumping was described as being due to high friction between the finger and the screen. Instead of sliding, their fingers started to move by small jumps over the screen. No participants reported missing the 0.5-second pulse because of the jumps, because their fingers likely did not jump for such a long time. The jumps of the finger could however not be recorded, because they were not visible in the time series data of either the IR sensor or the force sensors. The IR sensor likely still recorded the finger jumping over the screen since it records everything up to 1.4 mm above the screen. Next to this, the force sensors did not drop to near zero during these jumps, which made it too difficult to distinguish a jump from just a lower touching force. This is likely due to the force sensors not being fully unloaded before they were touched again. This caused them to only show a slight drop in force, instead of going to near zero. If the finger jumps could be recorded, however, the effect of these could be taken into account as well. This might have a large impact on the perception of the short electrovibration pulse.

Also, during the experiments conducted in this research, only vertical motion was used to simulate the external perturbations. This meant it was perceived as realistic air turbulence by the participants, but relatively easy to implement and perform. Using only vertical turbulence does imply that the turbulence only affects the vertical finger movement. This was the direction perpendicular to the finger movement direction. The effect on the vertical finger movement was amplified by the fact that the touchscreen was mounted almost vertically, with an 18-degree angle from fully vertical. This orientation was used because the screen was mounted on top of the existing touchscreens in the cockpit and it is a common orientation of touchscreens in vehicle cockpits. However, if the screen were mounted horizontally, the vertical perturbations would not cause finger motion on the screen, it would induce stronger normal force changes. To investigate the effects of the external perturbation direction and touchscreen orientation, future research could investigate what the effects of horizontal external perturbations are. Next to this, other touchscreen orientations could be investigated to see in which orientation the electrovibration is affected more by external perturbations.

In the experiment conducted during this research, only one frequency of electrovibration was used. A frequency of 100 Hz was used, which meant a frequency of 200 Hz was felt by the participants since frequency doubling occurs when a sinusoidal stimulus is used. This frequency is in the range of frequencies at which electrovibration is most easily felt [14], [27]. It is also found by AliAbassi et al. that the electrostatic force and the friction coefficient of electrovibration are highest at 250 Hz [30]. However, it was found in earlier research that lower frequencies and different waveforms provide different sensations. Therefore, different frequencies and waveforms of electrovibration in combination with turbulence could also be investigated in future research to see which frequency and waveform have the strongest effect.

Due to the difficulty in sensing the 0.2-second pulse, the starting peak voltage of 50 volts might have been too low for some participants. As visible in figure 5, several participants have a threshold higher than 40 volts. This is higher than the first 5 dB step, which is visible in figure 4 and comes to approximately 28.1 volts. Because the voltage had an upper limit at the starting voltage, it might be that their thresholds were higher than 50 volts, but they were locked below 50 volts. In future research, this upper limit could be removed, such that participants can have a threshold above 50 volts.

When regarding the findings concerning finger speed, force, and force change, it can be concluded that the slight increase in the perceptual threshold of electrovibration is due to the physical effects on the finger during turbulence, combined with a short electrovibration pulse. The same physical effects occur during the longer electrovibration pulse conditions, but the effect is not present.

## 5 Conclusion

In this study, we investigated the effects of external perturbations on the perception of electrovibration. We found that short-duration electrovibration stimuli are ineffective due to the disruptive effects of perturbations. These disruptive effects include an increase in involuntary finger movement and a higher normal force fluctuation. However, longer-duration pulses provide robust tactile perception even under challenging conditions, making them a viable solution for touchscreen interactions in vehicles. Tactile masking does not seem to affect the perception. In combination with a short pulse length, turbulence causes an increase in absolute threshold, although the average force, force change, and finger speed are similar during these conditions compared to the longer electrovibration pulse conditions. It can therefore be concluded that if electrovibration should be used in vehicle cockpits during external perturbations, longer durations of electrovibration should be used. This means that if electrovibration is used to render buttons or sliders, their size (therefore their pulse duration) should be big enough to produce stimuli longer than 0.2 seconds. If stimuli equal to or longer than 0.5 seconds are used, however, turbulence has hardly any effect on the perception of electrovibration, according to the results of this research. Using short pulses of electrovibration to simulate ridges is not advised, they will likely be missed, especially during turbulence. With this knowledge, future research could focus on the effect of electrovibration on the task performance of touchscreen users during turbulence. After investigating this, we could be one step closer to the use of electrovibration as a solution to the negative effects of BDFT on touchscreen users.

## Acknowledgments

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## Appendix A
## Experiment briefing & Informed consent form

The experiment briefing and informed consent form were sent to every participant before the experiment. Contact information was redacted for privacy concerns.

# Experiment briefing

**Effect of turbulence on perception of electrovibration**

You have been asked to take part in the experiment regarding the effect of turbulence on perception of electrovibration. This experiment will be performed by Dies Vuik, a TU Delft MSc student, under the supervision of Dr. Yasemin Vardar and Dr. ir. Daan Pool. Information about the experiment is provided in this briefing letter.

**Background of the experiment**

Using touchscreens in vehicle cockpits provides lots of advantages compared to using mechanical buttons or knobs, but a big disadvantage of using touchscreens is the lack of physical feedback provided by the screen. A touchscreen consists of a glass plate, which feels slippery when touched. During external perturbations in vehicle cockpits, like turbulence in aircraft or bumpy roads in cars, it becomes difficult to use the touchscreen as intended. This is due to an effect called biodynamic feedthrough. This effect is the involuntary movement of limbs due to external perturbations. In this experiment, a touchscreen which provides haptic feedback in the form of electrovibration is tested. This haptic feedback increases the friction felt by the touchscreen user, which makes the screen feel "sticky", and could in that way help in using the touchscreen during external perturbations.

**Purpose of the research**

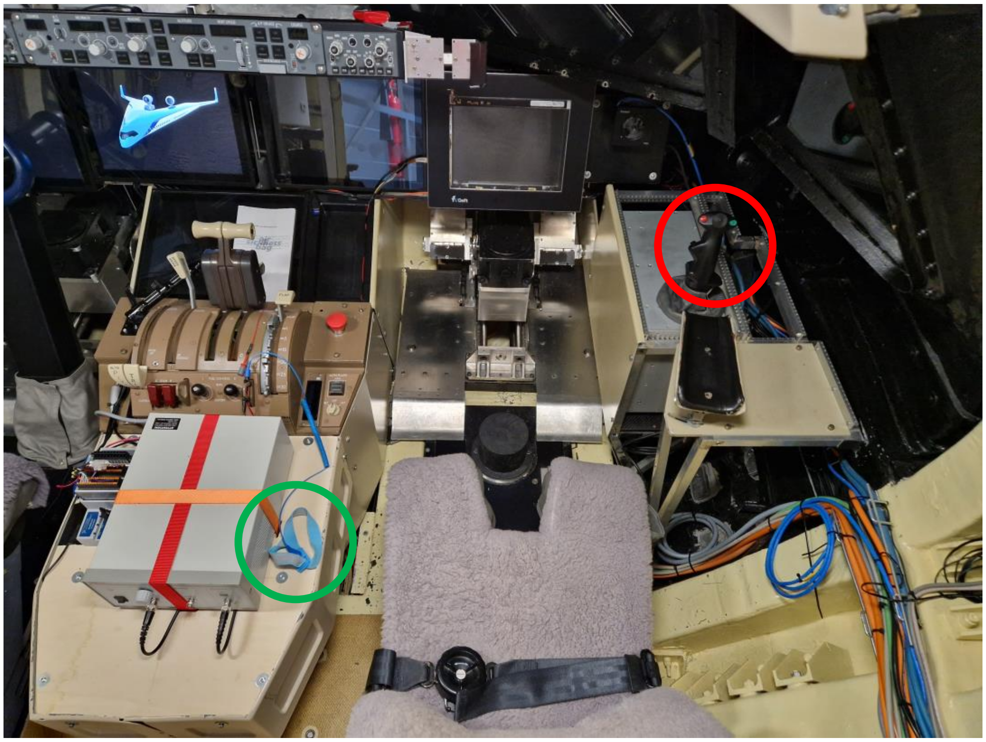
The goal of this research is to investigate what the effects of external perturbations in the form of air turbulence are on the perception of electrovibration. The data will be used for scientific studies and publications.

**What does participation in the experiment involve?**


The experiment will take place in the SIMONA Research Simulator at the faculty of Aerospace Engineering of TU Delft, visible in the figure on the right. You will be seated and trapped into the seat by a 5-point safety harness.

In order to have a stronger sensation of electrovibration, a grounding wristband has to be worn on your non-dominant arm during the experiment. The wristband is visible in the green circle in the figure on the next page.

During the experiment, vertical motion is used to simulated turbulence. During this vertical motion, you are required to move your finger following a moving ball over a touchscreen twice for 4 seconds. The first interval will show a red ball and the second interval will show a green ball. In between these two intervals there is a break of 3 seconds. One interval will contain an electrovibration stimulus and the other interval will not contain any stimulus. After these two intervals there will be time to make a choice on which interval contained the stimulus via the sidestick in the cabin. The sidestick is visible in the red circle in the figure below. To choose the first interval, press the red button. To choose the second interval, press the green button. To continue with the next trial, press the trigger button on the back of the stick.



The experiment uses a staircase method, using this method means that there is no specified number of trials for a session. The amount of trials depends on the answers given by you. It is however estimated that one session will take approximately 20 minutes. There will be six sessions, with different conditions. This will result in a  approximate total time of 2-2.5 hours for the complete experiment. There will be two scheduled 15-minute breaks, one after two conditions and one after four conditions. An extra break in between conditions is allowed, notify the researcher if this is needed.

**Procedures for withdrawal from the study**

Your participation in this study is fully voluntary, and you are free to end it at any time, including in the middle of the experiment, by telling the researcher using the microphone on the pilot's headset you will have to wear. You have the right to ask for personal data access, correction, or deletion. You are not required to provide justification for your choice. To do this, get in touch with the researchers using the details provided in at the end of this document.

**Confidentiality of data**

It is required to gather and use the following personal information for this investigation: Name, age, hand dominance and gender. We shall take the necessary security precautions to protect your personal information and ensure its confidentiality. This means that your data will be kept in a safe storage environment at TU Delft at all times. Only the researchers will have access to the data. All information will be handled in confidence and kept in a participant-only database. Only on the informed consent form will your name be connected to a participant number. The informed consent form will be kept in a separate, secure location and kept digitally. Your information will remain private in this manner. The only people that know your participant number are the researchers.

The personal data will be retained for linking your participation number to the informed consent, to facilitate the erasure of personal details, if you request.

The findings of this investigation will possibly be reported in upcoming scientific journals. Any publications (master's thesis report, scientific papers, reports) about the study will never include your participant number or name.

**Researcher's names, telephone numbers, and email addresses:**

**Dies Vuik:**

**Yasemin Vardar:**

**Daan Pool:**

# Consent form for electrovibration during turbulence

**Researcher:** Dies Vuik
**Title of research:** Effects of external perturbations on perception of electrovibration
**Supervisors:** Yasemin Vardar & Daan Pool

| PLEASE TICK THE APPROPRIATE BOXES | Yes | No |
|---|---|---|
| **A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION** | | |
| 1. I have read and understood the study information or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction. | ☐ | ☐ |
| 2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason. | ☐ | ☐ |
| 3. I understand that taking part in the study involves filling a questionnaire via a computer, which will be stored anonymously. | ☐ | ☐ |
| **B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)** | | |
| 4. I understand that taking part in the study involves the following risks: limited discomfort, dizziness or nausea. I understand that I am able to ask to stop the experiment at any point. | ☐ | ☐ |
| 5. I understand that personal information collected about me that can identify me will not be shared beyond the study team. | ☐ | ☐ |
| **C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION** | | |
| 6. I understand that after the research study the de-identified information I provide will be used for reports and or publications and that the researcher will not identify me by name in any report or publication that will result from this experiment. | ☐ | ☐ |
| **D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE** | | |
| 7. I give permission for the de-identified answers that I provide to be archived in so it can be used for future research and learning. | ☐ | ☐ |
| **E: Safety** | | |
| 8. I confirm that the researcher has provided me with detailed safety briefing and operational instructions to guarantee that the experiment can be performed in line with the current TU Delft COVID-19 guidelines and that I have understood these instructions, and that this experiment shall at all times follow the TU Delft guidelines | ☐ | ☐ |
| 9. I understand that this research study has been reviewed and approved by the TU Delft Human Research Ethics Committee (HREC). I am aware that I can report any problems regarding my participation in the experiment to the researchers using the contact information below. | ☐ | ☐ |

**Signatures**

____________________________ ___________________________ _________
Name of participant Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ___________________ _________
Researcher name [printed] Signature Date

Study contact details for further information:

Dies Vuik

# Appendix B
# Data analysis

## B.1 Normal force

During the experiments, four force sensors were attached to the four corners of the capacitive touchscreen. The force sensors used were: FSG020WNPB, Honeywell Inc. A close-up of the touchscreen inside of the frame attached to the force sensors is shown in figure 10. Here, the IR sensor on top blocks the view of the two upper force sensors.

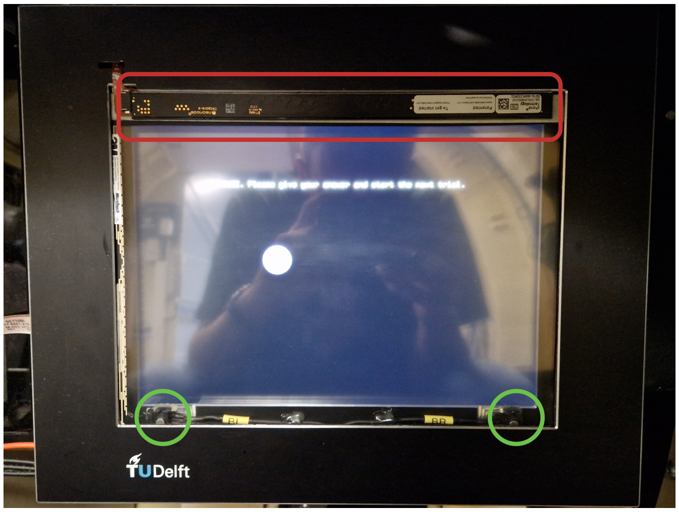


Fig. 10: A close-up of the touchscreen encapsulated by the frame. Two of the four force sensors are visible in the green circles at the bottom of the screen, the other two are below the IR sensor(NNAMC2300PCEV, Neonode Inc.) in the red rectangle on the top of the screen.

These force sensors have a range of up to 20 N, this was done to make sure that the clamping force and touching force of the touchscreen users would be inside of the range of the force sensors, so they would not overload. To get Newtons as the output of the force sensors, the sensors were calibrated. This was done by putting weights on the sensors and measuring the output voltage at that specific weight. The results for the four different sensors are shown in table 1.

| | Force (N) | | | | | |
|---|---|---|---|---|---|---|
| Sensor | 0.5 | 2 | 5 | 10 | 15 | 20 |
| 1 (top left) | 4.1e-3 | 0.018 | 0.041 | 0.088 | 0.132 | 0.165 |
| 2 (top right) | 3.1e-3 | 0.0165 | 0.042 | 0.090 | 0.133 | 0.170 |
| 3 (bottom left) | 3.0e-3 | 0.0160 | 0.043 | 0.085 | 0.128 | 0.164 |
| 4 (bottom right) | 3.3e-3 | 0.0168 | 0.041 | 0.090 | 0.132 | 0.173 |

TABLE 1: All four sensor output voltages for different force intensities.

The values from the table were used to make a linear fit, which approximates the force for any voltage. The data points and fit are shown in figure 11. The final fit was according to the following equation.

$$F_N = 1.16619823 \cdot 10^2 \cdot F_V + 1.42033931 \cdot 10^{-2} \quad (3)$$

Next to calibrating the force sensors, the clamping force from the frame had to be subtracted from the force measurements. This was done for every individual sensor, before

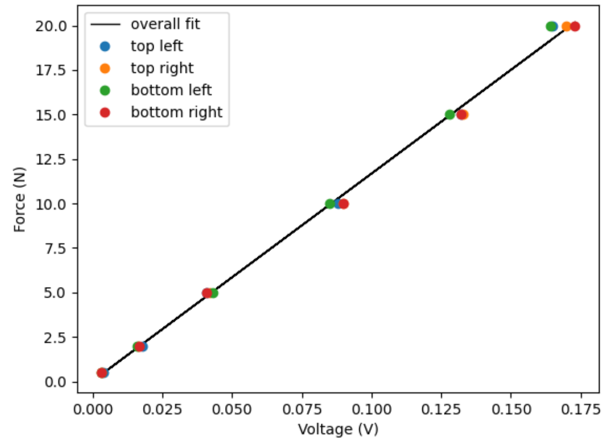



Fig. 11: The calibration fit with the 24 data points measured during the calibration.

the conversion to Newtons. The clamping force in Volt per sensor is visible in table 2. The average clamping force is 4.15 N.

| Sensor | Clamping force (V) | Clamping force (N) |
|---|---|---|
| 1 | 0.038 | 4.4458 |
| 2 | 0.028 | 3.2796 |
| 3 | 0.041 | 4.7956 |
| 4 | 0.035 | 4.0959 |

TABLE 2: The clamping force of the frame in Volt and Newton per sensor.

After these steps, the weighted average normal force was calculated. This was done by tracking the position of the finger, dividing this position by the full height and width of the screen to get the x and y factor, which goes from 0 to 1 from left to right and top to bottom. With these factors, the weighted forces can be calculated. This is done by the following equations, where $factor_x$ and $factor_y$ denote the factors, $tl$ denotes the top left sensor, $tr$ the top right sensor, $bl$ the bottom left sensor, and $br$ the bottom right sensor. $F_x$ and $F_y$ denote the weighted forces and $F_N$ denotes the final weighted average force.

$$F_x = factor_x(tr + br) + (1 - factor_x)(tl + bl) \quad (4)$$

$$F_y = factor_y(bl + br) + (1 - factor_y)(tl + tr) \quad (5)$$

$$F_N = \frac{F_x + F_y}{4} \quad (6)$$

This weighted average causes the force sensors that are closer to the finger to have more impact on the force. For example, if $factor_x$ equals 0.8, it means that the finger is much closer to the two right sensors than the two left sensors. If this is not taken into account, the lower values that are registered from the left sensors will contribute the same amount as the right sensors. In contrast, they do not read as much accurate force because they are much further away from the finger. This effect is counteracted by the procedure described above. The resulting force is plotted in figure 12. This plot shows the force over all trials of one experiment. On the horizontal axis, the timesteps are shown. The force is sampled at 2000 Hz.

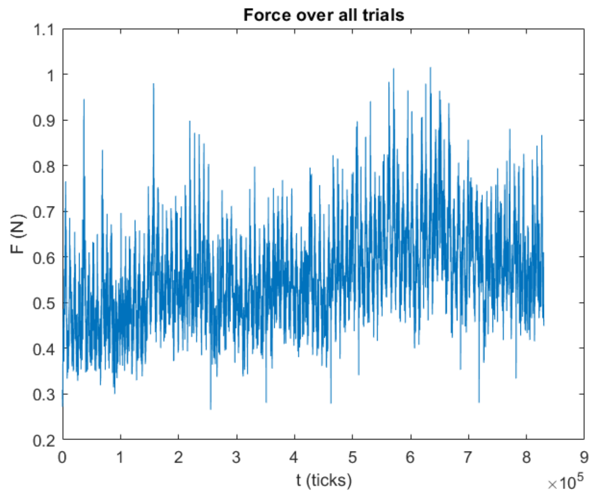



Fig. 12: The weighted average force over all trials of one experiment.

The raw force data was noisy, however, with a lot of high-frequency noise being present for the entire time series. This was not necessarily a problem for the average force measurements, but rather so for the force change measurements, which was the force signal differentiated over time. Because of the high-frequency noise, the force change would become much higher than realistically possible. The noise was filtered by using a zero-phase digital second-order low-pass Butterworth filter. This filter uses the "filtfilt" function of Matlab and uses a half-power frequency of 0.05 Hz. This was chosen to filter out the high-frequency noise, but keep the actual peaks from the touches. A representation of the filtering is shown in figure 13, where a zoomed-in section of the force signal is presented. Here the effect of the filter is visible. The high-frequency is filtered out, but the actual force differences remain present. A lower half-power frequency would result in more filtering, but this caused the actual force peaks to be filtered out as well. This is not the case with the current half-power frequency.

An effect that was found later on in this research, was the direct effect of the turbulence acceleration on the normal force data. This was visualized by plotting all the first intervals as one line and all the second intervals as another. The first and second intervals always have the same turbulence, so this would mean the plots would overlap a lot. The effect of turbulence on the normal force is shown in figure 14. Here, note that both the first and second interval curves show very similar peaks, which differ for each trial. This is found to be the effect of the accelerations of the turbulence. Plotting the turbulence on top of this force plot is however not that easy, since the turbulence is sampled with 100 Hz and the force with 2000 Hz, and all three variables have different tick values. Because of this and the time at which this effect was found, it was not possible to properly investigate the effect. However, in future research, this is something to be investigated.

Still, the overlap of the two curves could be measured by taking the integral of both and subtracting them. This

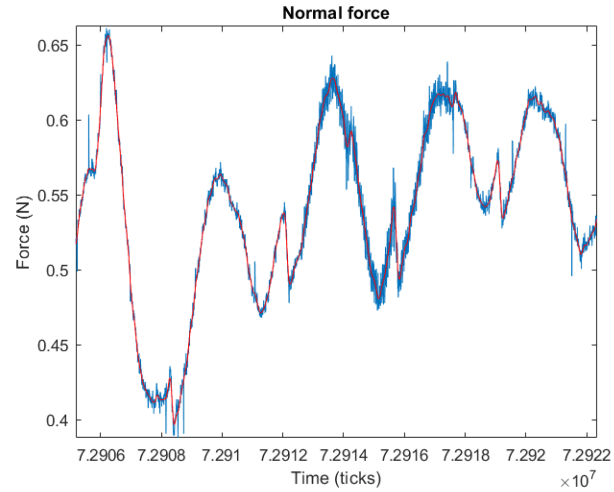



Fig. 13: A section of the force signal, with the raw data depicted by the blue line and the filtered signal depicted by the red line.

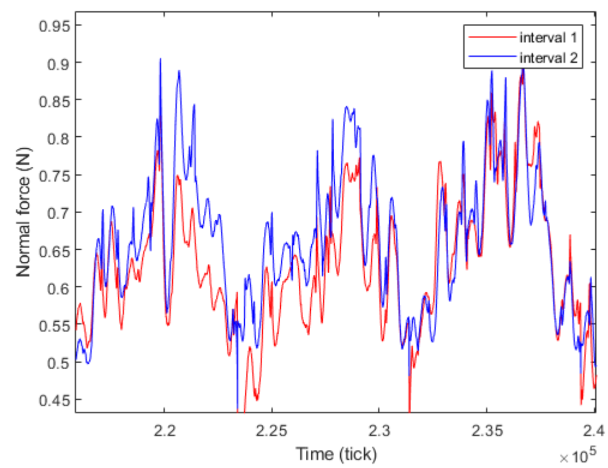



Fig. 14: A section of the force signal where the overlap due to the turbulence is visible.

was done for all participants and all staircases. This data is also plotted in boxplots in figure 15. In this figure, a clear increase in overlap is visible going from the no turbulence to turbulence conditions, however, no significant effect was found when analyzing this data with generalized linear mixed models. Combined with the turbulence accelerations, however, this might change the look of the data and could result in some significant effects.

### B.2 IR sensor

The Neonode IR sensor (NNAMC2300PCEV) was mounted on top of the electrovibration screen by using a strip of double-sided tape. After it was attached, it was checked if the electrovibration would cause interference with the sensor and it was found that this was not the case. It was found that the IR sensor can sense six different touch events, including tap, swipe, pinch-to-zoom, and rotate. It was found that on some occasions, the sensor would output

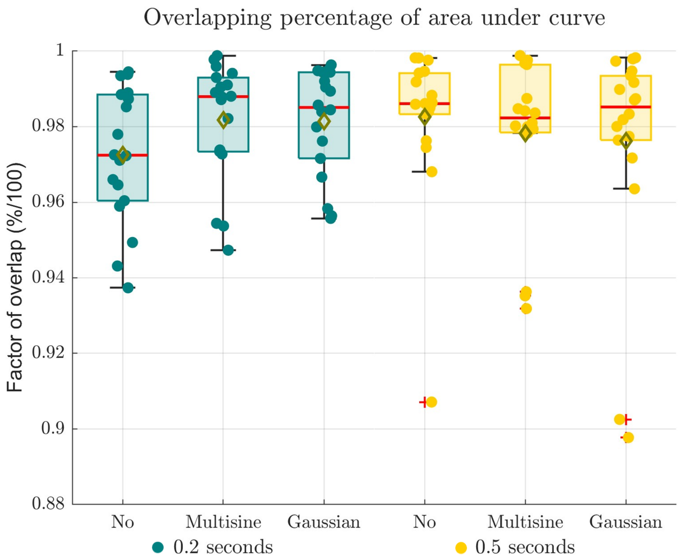



Fig. 15: Boxplots of the percentage of overlap between normal force curves.

touch events other than the tap or swipe events. This was filtered out in the reading code, where only the single-finger touch events were read. This filtered out some touch noise which appeared due to the double-finger touch events appearing. After this, the data was collected and analyzed. First, the finger data had to be filtered. For some runs, data would be found outside the screen range. This was not actual touch data, which was confirmed by testing. It was found that touching the frame below the screen, shown in figure 10 would not activate the sensor. Nevertheless, sometimes data would be measured outside the screen. The reason for this is unknown so far. The screen from the sensor to the frame at the bottom was measured, after which the sensor values at these edges were read. The width of the screen was found to be 255 mm, with a height of 177 mm. The corresponding touch sensor values were 65535 and 52993. These values were converted to mm, to look at the finger speed in mm/s. The filtered and converted signal was plotted in figure 6. After the filtering and conversion to mm, the finger speed is calculated by differentiating the finger position data. This was done individually for the horizontal and vertical finger positions.