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► **To cite this version:**

Corentin Bernard, Jocelyn Monnoyer, Sølvi Ystad, Michael Wiertlewski. Eyes-Off Your Fingers: Gradual Surface Haptic Feedback Improves Eyes-Free Touchscreen Interaction. CHI '22: CHI Conference on Human Factors in Computing Systems, Apr 2022, New Orleans, United States. pp.1-10, 10.1145/3491102.3501872 . hal-03658982

HAL Id: hal-03658982

<https://hal.science/hal-03658982>

Submitted on 4 May 2022

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Eyes-Off Your Fingers: Gradual Surface Haptic Feedback Improves Eyes-Free Touchscreen Interaction

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ABSTRACT

Moving a slider to set the music volume or control the air conditioning is a familiar task that requires little attention. However, adjusting a virtual slider on a featureless touchscreen is much more demanding and can be dangerous in situations such as driving. Here, we study how a gradual tactile feedback, provided by a haptic touchscreen, can replace visual cues. As users adjust a setting with their finger, they feel a continuously changing texture, which spatial frequency correlates to the value of the setting. We demonstrate that, after training with visual and auditory feedback, users are able to adjust a setting on a haptic touchscreen without looking at the screen, thereby reducing visual distraction. Every learning strategy yielded similar performance, suggesting an amodal integration. This study shows that surface haptics can provide intuitive and precise tuning possibilities for tangible interfaces on touchscreens.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; *Touch screens*; Auditory feedback; • **Hardware** → **Tactile and hand-based interfaces**.

KEYWORDS

Haptic feedback, surface haptics, learning, multimodality

ACM Reference Format:

Corentin Bernard, Jocelyn Monnoyer, Sølvi Ystad, and Michaël Wiertlewski. 2022. Eyes-Off Your Fingers: Gradual Surface Haptic Feedback Improves Eyes-Free Touchscreen Interaction. In *CHI Conference on Human Factors in Computing Systems (CHI '22)*, April 29-May 5, 2022, New Orleans, LA, USA. ACM, New York, NY, USA, 10 pages. <https://doi.org/10.1145/3491102.3501872>

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1 INTRODUCTION

Interacting with machines often consist in selecting programs or adjusting parameters, such as turning a knob to increase the volume, or moving a slider to set a program on a dishwasher. The physicality of these primitive interfaces is slowly disappearing in favor of versatile touchscreens, which can combine thousands of operations in a single unit. Touchscreens have the advantage of allowing reprogrammable tactile inputs and co-localized visuals. However, the generalization of such interfaces also come with an important trade-off on the type of feedback they provide to the user. A well-designed mechanical knob provides distinctive haptic responses, via its 3 dimensional shape when searched for, and via its mechanical impedance –the motional response to dynamic forces– when operated, which is pivotal to guide the user into reaching and operating the knob. On the other hand, the featureless flat pane of glass of a touchscreen provides no haptic cues on the location of the interface, nor on its operation. As a consequence, interface designers provide visual cues –progress bars, numerical values, or sliders– or auditory cues –clicks– as a way to indicate the progression of a setting change in response to the user’s motion. However, relying on visual or auditory modalities is often not suitable or even possible. For example, while driving, the use of dashboard screens causes visual distraction, and in dark environments visual cues might not even be available. Auditory feedback can also be degraded due to noisy environments.

Surface haptics has emerged as one potential solution to restore tangibility to touchscreens. It creates haptic sensations directly onto the user’s fingertip by modifying the friction between the skin and the glass plate. Controlling friction can be achieved either using ultrasonic vibration [8, 42, 43] or electroadhesion [3, 37, 41], and by modulating the friction force as a function of the position on the screen, sensations of textures and shapes can be recreated [4, 16, 25]. Creating zones of low friction can also help in guiding the user to a given target point, improving the information capacity of the user [12, 23]. Textural effect produced by dynamically varying friction as a function of the users’ position can assist the discrimination of direction [5, 9, 21]. Gradual frictional haptic feedback is a promising avenue for reducing visual attention. It is however unclear how such congruent visuo-haptic stimulations affect the learning of new gestures.

Here, we show that in the particular interaction of tuning an integer value, surface haptics can significantly improve the interaction. Such adjustment tasks are found when tuning the ventilation

power, changing a sound level, raising the height of window blinds, and so on. In this paper, the controlled parameter is referred to as the *setting*, noted γ , which can take a value between 0% and 100%. The interaction consists of adjusting the setting by sliding the finger up or down, which is made possible through clutching movements, where the finger hovers over the plate back to the initial position. As the setting changes, the user feels a synthetic texture on the haptic surface, whose spatial frequency (or number of ridges per millimeters) is proportional to the value. Through learning and practice, the user can learn how to associate the setting to the state of the texture, and use this information to adjust the value on an absolute scale. We propose different learning strategies with visual and auditory stimuli to assess how subjects adapt to haptic feedback with the help of other modalities: a visual feedback rendered as a slider, and an auditory feedback for which the pitch and beat are tied to the value. To study the effect of the guidance hypothesis which states that learning with extra cues might lead to a poorer transfer to the actual task [38], we added two more conditions where the visual or the auditory feedback slowly fades out from trial to trial. Lastly, we added a fifth control condition, where only haptic feedback was present.

To evaluate the proposed interaction, we constructed an experiment in which subjects are asked to adjust the setting to a target value as quickly and precisely as possible, with first a learning session and then an evaluation session. The performance of the subjects are measured in terms of *completion time* and *adjustment error*. Based on these metrics, we compare the efficiency of the five different learning strategies in helping the subject to retain the interaction during the evaluation phase. We found that, after training, the subjects improved their setting performance, regardless of the learning strategies.

2 RELATED WORKS

2.1 Eyes-free interaction

Haptic feedback of everyday objects reduce the need for visual attention during interface control. Using force feedback knobs and sliders, Snibbe et al. [39] introduced multiple rendering strategies to provide physical feedback to continuous interactions, for example while manipulating media such as video, audio or computer graphics. Haptic event count is a common communication strategy. This interaction is for example experienced in mouse wheels. Applying this approach to interactions with touchscreens proves effective to help users set a value or select a menu by counting the number of vibration ticks they can feel from a vibrotactile surface [24] or with actuators directly on the wrist [44]. While these methods are based on our temporal perception and segregation of tactile events, other strategies exploit our tactile spatial acuity [17] by conveying information through the localization of vibrations on the body. The perceptual motion of a vibration around the wrist enables the user to perform pointing, selection and drag-and-drop tasks without vision. In the present approach, users actively explore a texture with evolving spatial periods to set a given value. The access to the haptic information is directly linked to their movement, mimicking real world sensorimotor interactions.

2.2 Haptic feedback for pointing tasks

Setting a slider can be considered as pointing to the desired value. Human performance when reaching a target is well quantified by Fitts' law [15]. This seminal finding predicts the time required to rapidly move to a target as a function of the size and the distance of the target, which together define the index of difficulty. This discrete model was extended to the continuous case of following a tunnel, by the steering law [1]. These models initially considered the integration of visual cues to guide participants' motion. Recently, it has been shown that the addition of haptic feedback can also significantly reduce the time it takes, effectively illustrating that the difficulty of the task is reduced in the presence of an additional type of feedback [12, 20, 23]. These studies considered the simple case of a binary feedback, where friction was low everywhere but high on the target, or vice-versa. However, binary feedback only guides the user when a specific target is reached and not during the entire motion. Therefore, this kind of feedback is ill-suited to enhance tuning tasks, since the value of the setting is not known in advance by the rendering algorithm. For this purpose, continuous feedback, where the amplitude or the frequency evolves continuously, has shown potential for guiding users [21].

2.3 Auditory guidance using sonification

Other forms of feedback have also shown promising results for guiding the user on a touchscreen, in particular auditory feedback via sonification. Sonification is the use of non-speech auditory feedback to convey information to the user [2]. It can be relevant in interface manipulation because the auditory system performs well at analyzing dynamic information and recognizing temporal and frequency patterns. It has even been shown that gesture sonification can bias our movements [40]. The main perceptual attributes of a sound, i.e. pitch, loudness, tempo, and timbre (brightness, inharmonicity and roughness), have been compared in their capability of guiding the user gesture in a target experiment [32]. These attributes were used to sonify the distance to the target, which means that subjects had to find the position of the lowest pitch or the fastest tempo, for example. Participants were faster and more precise with sonification strategies that varied in pitch and tempo. Pitch sonification is also the preferred strategy for mid-air gesture interfaces [10]. Moreover, the performance at two-dimensional path following tasks with audio and haptic guidance are similar across modalities, suggesting that the presence of any type of feedback is enough to guide the control of motor commands [13, 36].

2.4 Skill acquisition with multimodal feedback

Learning a new interaction with an interface is closely related to learning a new gesture, since a subtle coordination between sensory input and muscle output has to be found. We drew inspiration from the literature on motor learning to design our training method, with a particular attention towards methods related to practice and refinements of new skills [31]. Augmented feedback, through the use of visual, auditory or haptic modalities, has been shown to effectively enhance motor learning [38]. Two types of feedback are considered: the *concurrent feedback*, which is a real-time feedback presented during the task execution that helps to perform

the gesture, and the *terminal feedback*, which present the performances after the completion of the task. This feedback can be a display of the error, the completion time or the trajectory. Concurrent feedback and terminal feedback are most effective during the early learning phase. However, to develop a persistent internal representation of the task, feedback frequency and intensity should be progressively decreased [22]. Indeed, the sudden removal of a feedback can cause a significant degradation of performance [19]. In [35], authors compared the effect of no feedback, full visual feedback or weak visual concurrent feedback (with low contrast), during the acquisition phase. They found that the latter leads to better pointing performance in the transfer phase when no more visual feedback is provided. By mitigating the appropriation of the guidance dynamics into the task dynamics, the assistance can progressively decrease during the training session [33].

3 INTERFACE AND HAPTIC SIGNAL

3.1 Interaction design

The interaction that we propose is performed on an inclined touchpad presented in Figure 1.a. It mimics new interfaces that emerge in automobile cockpits, with a touchpad on the driver’s right armrest. The touchpad provides control of the graphical dashboard display by sliding gestures. The interaction focuses on the use case of an absolute setting of a value, i.e. reaching a desired value, as opposed to a relative setting that consists of increasing or decreasing the value by a certain amount. Clutching interaction is implemented to virtually increase the physical space of the touchpad and extend the setting range without loss of adjustment precision. Clutching has been shown to provide better performances than continuous gestures in some cases [27]. The sliding gestures are performed in the vertical direction, from top-to-bottom to increase the setting value and from bottom-to-top to decrease it, as if interacting with a vertical carousel whose numbers increase in the upward direction. We chose to use ultrasonic friction-modulation rather than vibrotactile rendering for its more precise sensation delivery. Indeed, the just-noticeable difference of vibration frequencies (i.e. the lowest frequency difference to perceive a change in vibration) is between 18% and 20% [34] whereas it is between 6% and 11% for spatial frequencies of gratings [28]. An illustration of the illusion that is produced by the haptic feedback is shown in Figure 2.a.

3.2 Surface haptic display

The touchpad, presented in Figure 1.a, is a custom-made haptic surface actuated with ultrasonic friction modulation. The workspace is a $105 \times 22 \times 3.3$ mm glass plate. This size was chosen because it is technically easier to render powerful feedback on a plate of such dimensions rather than on a touchpad with conventional width, and it does not disturb one-dimensional vertical gestures. The position of the finger on the plate is measured at 400 Hz with an optical sensor (NNAMC1221PC01 Neonode Touch Sensor Module) connected to a microcontroller (Teensy 3.5). The microcontroller extrapolates the finger position at a frequency of 10 kHz and outputs a modulating signal according to the finger position and the friction map of the haptic stimulus, as presented in Figure 1.b. The carrier signal, a 35 kHz sine wave, is created by a function generator (BK Precision 4052) and amplitude-modulated by the analog signal

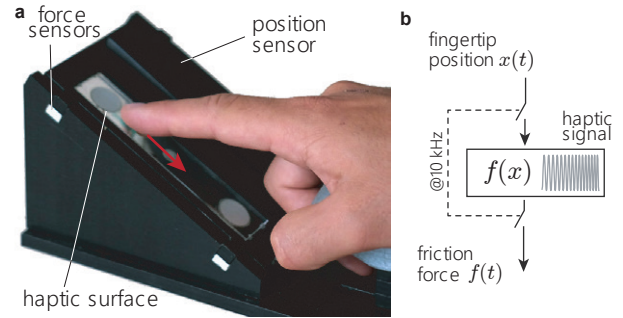


Figure 1: (a): Bespoke haptic touchpad used in the study. Users can explore the vertical surface and feel bumps and holes via ultrasonic friction-modulation. (b): The finger position is tracked in real time to update the frictional force according to the haptic signal.

provided by the microcontroller. The resulting signal is then amplified 20-fold (WMA-100, Falco Systems) to drive two piezoelectric actuators glued to the glass plate. Modulation of the amplitude of vibration of the glass plate induces friction variations between the finger and the plate during the tactile exploration as presented in Figure 2.d. The presence of the finger on the plate is detected with 2 capacitive force sensors (CS8-1N, Cal 8mm diameter, 1N/0.22lb force, SingleTact). The microcontroller is connected to the graphical interface with USB serial communication. The setting γ , the finger position, the finger velocity v_{fing} , and the spatial frequency of the haptic feedback ν are thus transmitted in real time and recorded.

3.3 Haptic signal

The haptic feedback consists in a sine wave of friction modulation, which spatial frequency evolves gradually with the setting. The choice of the mapping between the spatial frequency and the setting is paramount to create an intuitive interaction. We here propose to create this mapping with an exponential function derived from Weber-Fechner’s law [14], which states that the sensation varies as the logarithm of the excitation. The Weber-Flechner law applies to the perception of the spatial frequency of real gratings [28, 29] and was verified for friction modulated textures with informal pilot studies. In our design, the spatial frequency varies exponentially with the setting value, causing the sensation to evolve linearly with the setting value. For example, due to this design, the difference between the two textures at $\gamma = 30$ and $\gamma = 35$ is as clearly noticeable as between the two textures at $\gamma = 70$ and $\gamma = 75$, despite the underlying difference of spatial frequency is six times more important in the $\gamma = 70$ case.

First, the setting γ evolves with the finger swipes, and the variations of the setting $\Delta\gamma$ are proportional to the finger displacement Δx (in mm) by a factor $\alpha = 1/3 \text{ mm}^{-1}$:

$$\Delta\gamma = \alpha\Delta x \quad (1)$$

This relationship is illustrated in Figure 2.b. A 3 mm displacement of the finger on the interface induces a change of the setting value of 1. The haptic gradient feedback is a spatially encoded signal, in which the spatial frequency ν (in mm^{-1}) evolves with the setting γ

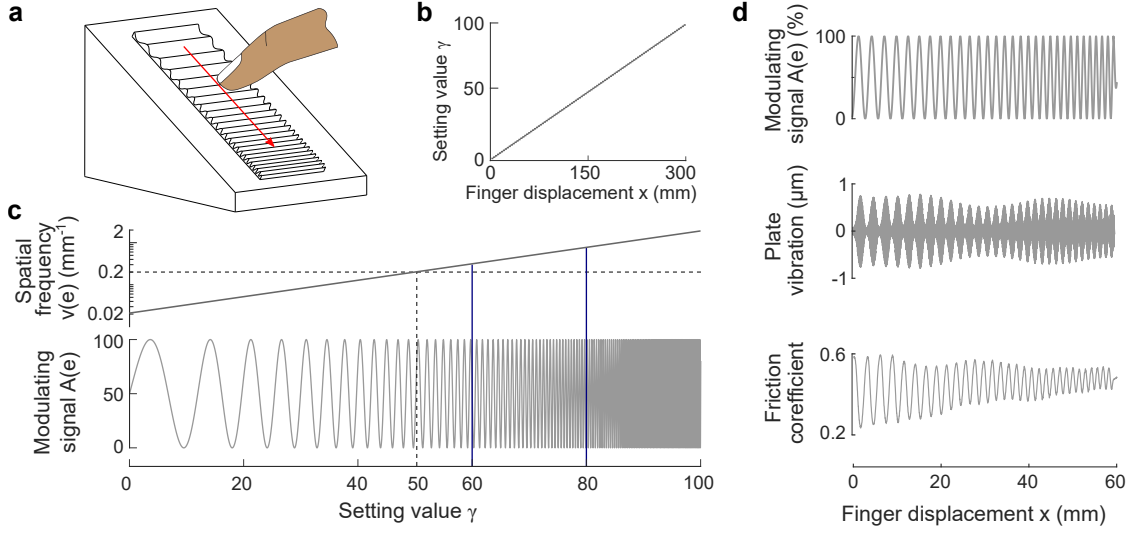


Figure 2: Description of the haptic feedback. (a): Illustration of the illusion produced by modulating fingertip friction on the haptic touchpad. (b): Relationship between the finger displacement and the setting. Theoretical representation with the whole range of variation (as if the whole range could be reached in one single movement). (c): Haptic feedback and the evolution of the spatial signal frequency with respect to the setting. The two target values are shown in blue lines. (d): Example of the actuation during one typical 60 mm finger slide, from $\gamma = 40$ to $\gamma = 60$. The modulating signal (upper plot) pilots the plate vibration envelope (middle plot) that produces friction variations (lower plot). Friction measurements were made with an interferometric force sensor described in previous works [6, 7].

as the finger explores the interface. The spatial frequency can be considered as the number of ridges per millimeter. For the gradient evolution to be perceived equally along the frequency range, we adapted the spatial frequency to the Weber's Law. According to this law, the just noticeable difference (JND) $\delta\nu$ of the frequency is proportional to the initial frequency ν multiplied by a constant of proportionality g :

$$\delta\nu = g\nu \quad (2)$$

The constant g is the gradient value (in mm^{-1}) and represents how fast the spatial frequency changes when the finger moves. The variations of the spatial frequency of the grating ν are obtained by integrating (2) with respect to the setting:

$$\nu(\gamma) = \nu_0 \exp\left(g \frac{\gamma - \gamma_0}{\alpha}\right) \quad (3)$$

where $\nu_0 = 0.2 \text{ mm}^{-1}$ is the central spatial frequency which is reached when the setting is at half range, i.e. $\gamma = \gamma_0 = 50$. The modulating signal A that oscillates at the instantaneous frequency ν is then defined as follows:

$$A(\gamma) = \cos\left(2\pi \int_0^\gamma \nu(u) du\right) \quad (4)$$

The gradient value was fixed to $g = 0.015 \text{ mm}^{-1}$, an appropriate trade-off to ensure that users can feel the spatial frequency change over the distance of a typical finger slide ($>50 \text{ mm}$) [5], while allowing for fine-tuning of the setting value and respecting the limits of the device and of human perception in terms of spatial frequency bandwidth (≈ 0.02 to 2 mm^{-1}). The resulting haptic signal is presented in Figure 2.c.

4 USER STUDY: INTERACTION LEARNING

Since the interaction with haptic feedback requires training, we performed an experiment to investigate how well subjects can learn the task. We measured their performances after a training session, in which additional visual or auditory feedbacks helped the learning process.

4.1 Task

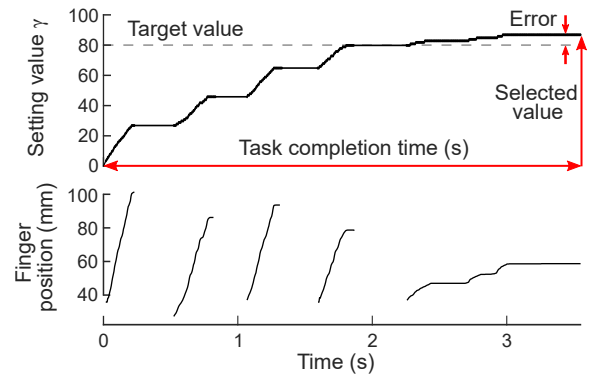


Figure 3: Setting and finger position variations for a typical trial (initial value $\gamma_i = 0$, target value $\gamma_t = 80$, haptic feedback only). The setting is increased by successive slides of the finger on the touchpad with clutching. The finger position is not measured during clutches. The 3 performance metrics are also presented.

Both the training session and the learning session were conducted on the same task. At each trial, the setting was randomly initialized at one of the five initial values $\gamma_i = 0, 10, 20, 30, 40$. Subjects were not explicitly informed of the initial value, but they could sense it from the feedback. It prevents subjects from basing their actions on proprioceptive cues only ("muscle memory" such as finger displacement and number of movements) that would bias the experiment. The target value, either $\gamma_t = 60$ or $\gamma_t = 80$, is displayed on the screen. By successive slides of the index finger on the touchpad with clutching, the subjects were asked to increase the setting until it reaches the target value as quickly and precisely as possible, as presented in Figure 3. They selected the final value by lifting the finger for more than two seconds. To achieve the task, subjects need to mentally associate the two target values to two spatial frequencies of the texture. The target values $\gamma_t = 60$ and $\gamma_t = 80$ correspond to gratings of spatial frequency $\nu_t = 0.31$ and $\nu_t = 0.77 \text{ mm}^{-1}$, respectively. The 5 initial values and the 2 target values were chosen arbitrarily after informal pre-tests, with the condition that target values should be sufficiently distant from the highest initial values ($\gamma_i = 40$) and the upper limit ($\gamma = 100$). As the haptic gradient is continuous, the feedback signal does not exhibit any particular behaviour for these values. We assume that the experiment would lead to similar results with other target values because the spatial frequency evolution is based on human discrimination capacity as explained in section 3.3. Subjects were asked to avoid reaching a too high value (above 100) to prevent any other proprioceptive biases. The 5 initial values and the 2 target values led to 10 task conditions. During the experiment, the task conditions were presented in randomized orders per block of 10.

4.2 Protocol and learning strategies

Participants sat in a chair in front of the computer on the experimental desk and wore headphones. After being informed about the experimental procedure, they placed their right hand on the wrist rest placed on their right-hand side. They were asked to interact with the touchpad with their right index finger. Before the experiment, subjects could interact with the touchpad without any feedback during 1 min to become familiar with the gesture. Then the experiment started with the learning session (or acquisition phase). This session was composed of 200 trials (20 blocks) of the task described in the previous section. The touchpad was actuated with the concurrent haptic feedback. At the end of each trial, subjects were informed about their performance by a digital display of the selected value on the graphical interface. This terminal feedback helped them correct themselves and improve their performance on a trial by trial basis. The haptic feedback can be enhanced with additional, auditory or visual, feedback. The five learning strategies were investigated with five groups of subjects following a between-subjects experiment, as presented in Figure 4.

The experiments ended with the evaluation session (or transfer phase) which was the same for each subject. It was composed of 40 trials (4 blocks), with the same task as in the learning session, with the haptic feedback only. No additional feedback or terminal feedback were presented. The whole experiment lasted for about 50 minutes.

4.3 Additional feedback

The additional visual feedback consists of a vertical slider on the graphical interface that moves up and down as the subject adjusts the setting value. It is similar to what we experience with everyday interfaces. For the *fading out Visual* condition, the contrast of the slider decreases progressively so that it becomes less and less visible and then disappears, as presented in Figure 4.

The additional auditory feedback is constructed by sonification (both pitch and tempo related) of the setting, the haptic friction signal and the finger velocity. The setting is sonified by a monochromatic tone whose frequency varies between 100 and 600 Hz (for $\gamma = 0$ to 100). The frequency is logarithmically mapped to the setting. The target values $\gamma_t = 60$ and $\gamma_t = 80$ correspond to pitch frequencies of 293 and 419 Hz, respectively. The sonification of the haptic friction signal is tempo-related and made by amplitude-modulations whose modulation frequency $f_{mod} = v * v_{finger}$ matches those of the haptic stimuli to ensure multisensory congruency between the two stimuli [5]. The resulting signal is illustrated in Figure 4. For the *fading out Audio* condition, the sound level decreases progressively and becomes less and less audible. Informal pre-tests measured the perceptual thresholds of the audio and visual stimuli to ensure that additional feedback became unnoticeable about halfway through the training session (trial number 100) under the fading out conditions.

The Max/MSP interface generates the visual and auditory feedback. Sounds were played through noise-cancelling headphones (3M PELTOR ProTac III) that also prevented any external auditory cue from the device.

4.4 Subjects

40 subjects, 14 females and 26 males, 34 right-handed and 6 left-handed, ranging from 20 to 54 years old (mean 27.9) participated in the study. They gave their informed consent before the experiment and the study was approved by the Ethical Committee. They were paid for their participation. Before the experiment, subjects washed and dried their hands and the touchpad was cleaned with an alcoholic solution. They were randomly assigned to one of the five learning strategy groups.

5 RESULTS

Task performances are assessed using three metrics: the final value, the error and the completion time, as presented in Figure 3.

5.1 Overall results

After training, participants were able to use the haptic cues to adjust the setting to $\gamma_t = 60$ or $\gamma_t = 80$. Boxplots of the distribution of the selected values obtained during each trial are shown in Figure 5a. The clear difference in the median of the two conditions demonstrates that subjects were successful in performing the task. A two-sample Student-Welch t-test with unequal variances validates the significant difference between the two target value conditions ($t=-27.5$, $df=1591$, $p=3.8 \cdot 10^{-136}$). We can observe that the target value at 80 was reached more accurately (median selected value: 80) than the target value at 60 (median selected value: 62.5), with the same variability (interquartile range: 13).

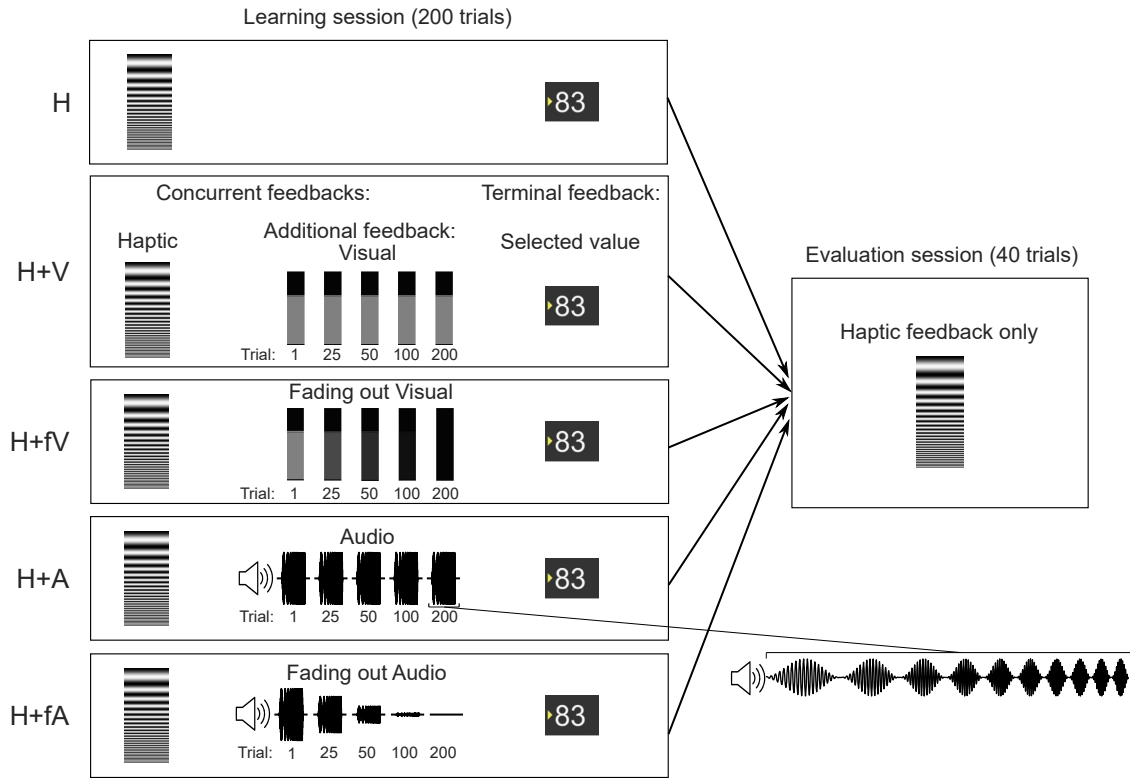


Figure 4: Illustration of the experimental protocol and the five learning strategies experienced by 5 groups of 8 subjects. Group conditions only differ by the additional concurrent feedback (auditory or visual) during the learning session. Haptic feedback is a gradient of spatial frequencies rendered with ultrasonic friction modulation technology. For the *Visual* condition, a slider is displayed on the graphical interface. For the *fading out Visual* condition, the slider contrast decreases until it becomes invisible around trial 100. For the *Audio* condition, the pitch and the modulation frequency of the sound are mapped to the setting value and to the haptic friction variations. For the *fading out Audio* condition, the sound level decreases until it becomes inaudible around trial 100.

Figure 5b presents the effect of the initial value on the setting error in order to control any possible proprioceptive biases. If the subjects had relied purely on the estimation of the distance covered by the finger on the interface, the selected value would have been underestimated for the lowest initial value and overestimated for the highest initial values, as illustrated by the grey line in Figure 5.b. Here, even if the initial value shows a significant effect on the setting error (one-way ANOVA: $F_4 = 19.9$, $p=5.4 \cdot 10^{-16}$), due to an overestimation for the $\gamma_i = 30$ and 40 initial values, this bias is much lower than the theoretical bias with proprioception only. It demonstrates that subjects succeeded in integrating tactile cues in their selection.

The task completion time is presented in Figure 5.c as a function of the setting distance between the initial and the target value $\Delta\gamma = \gamma_t - \gamma_i$. The task distance shows a significant effect on the completion time (one-way ANOVA: $F_6 = 12.8$, $p=3.3 \cdot 10^{-14}$). Subjects spent more time to adjust the setting when the target value was much greater than the initial value, as exhibited by the linear regression performed on the mean completion time $T = 0.035 \times \Delta\gamma + 2.42$ ($R^2 = 0.993$).

In summary, the results allow us to quantify the user performance. With haptic feedback only, subjects performed the task on average in 4.1 s with 8.1% of error (mean of the absolute value of the error and mean of the completion time on all subjects during the evaluation session, outlier trials excluded).

5.2 Learning strategy comparisons

We can compare the five learning strategies by looking in detail at the learning process. Figure 6 presents the learning curves for the five strategies, in terms of error and completion time. Trials are gathered by blocks of 10, with one of each target value and initial value condition in each block. Outlier trials are excluded thanks to the quartiles method (more than 1.5 interquartile ranges above the upper quartile or below the lower quartile) before averaging the trials' metrics in each block. The learning curves show how performances evolve during the training with respect to the learning strategy.

To characterize the evolution of the error, learning curves are fitted with power law functions $\gamma(k) = a \times k^{-b} + c$ that are typical of skill acquisition [30]. These functions are calculated for the 3

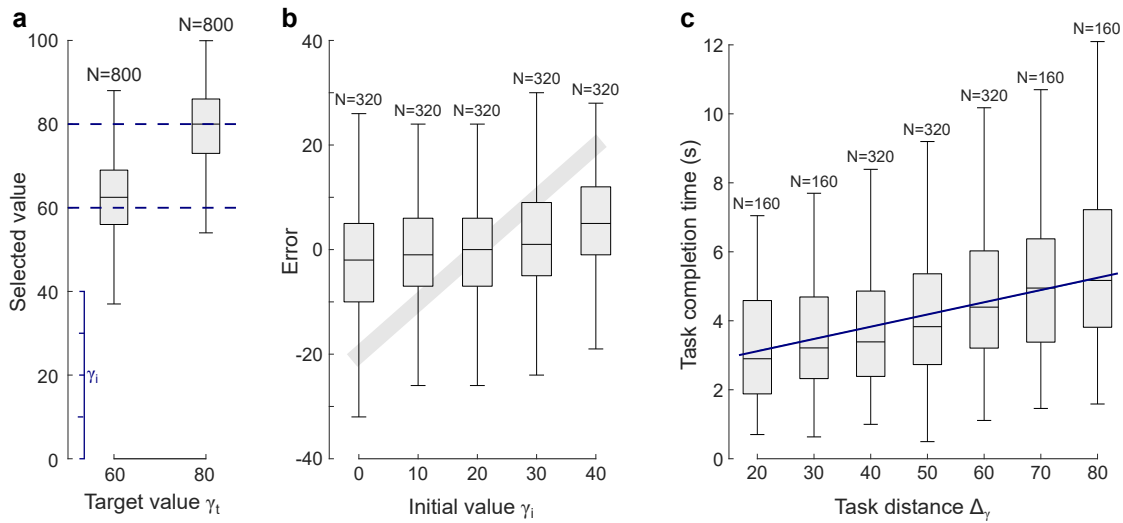


Figure 5: Results of the evaluation session. (a): Boxplot of the selected value for the two target value conditions during the evaluation session for all subjects. The targets are also displayed in dashed lines. The initial value range is plotted in blue. **(b):** Boxplot of the error on the selected value for the five initial value conditions during the evaluation session for all subjects. If responses were only based on proprioceptive cues, the error would follow the trend shown by the grey line in the background. **(c):** Boxplot of the task completion time as a function of the task distance ($\Delta\gamma = \gamma_t - \gamma_i$) during the evaluation session for all subjects. The mean completion time (with outliers exclusion) increases linearly with respect to the task distance, as proven by the linear regression presented in blue line ($R^2=0.99$).

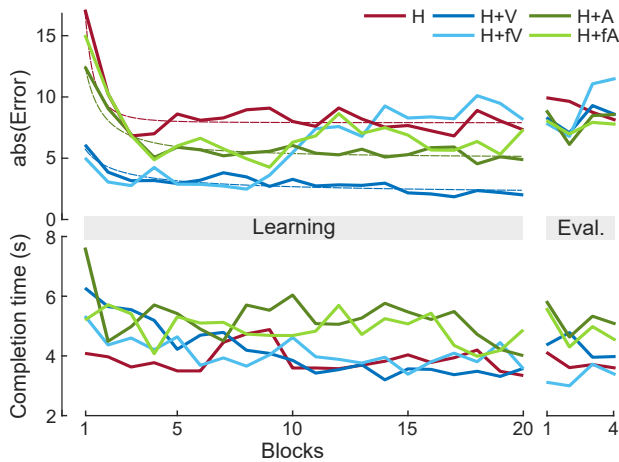


Figure 6: Learning curves for the five learning strategies. Performance metrics are averaged by blocks of 10 trials. The 20 first blocks are for the learning session, the 4 last blocks are for the evaluation session. Learning curves for strategies with permanent additional feedback are fitted with power law functions as displayed in dashed lines.

conditions with permanent feedback only. The parameter $a + c$ shows the error level at the beginning of the training and c the error level at the plateau. The parameter b reflects how quickly subjects improve their performances.

Subjects with haptic feedback only and additional auditory feedback start with a high error ($a + c = 17.1$ and 12.6 respectively) whereas it is much lower for subjects with visual feedback ($a + c = 5.8$). However, the error drops quickly for haptic and auditory strategies ($b = 2.7$ and 1.3 respectively) while it only slightly decreases for visual strategies ($b = 0.7$). After the initial improvement, the error remains stable for the 3 learning strategies with permanent feedback, with an error level of $c = 8$, 5 and 1.9 for the *Haptic*, *Audio* and *Visual* conditions, respectively. In contrast, for the learning strategies with feedback that fades out with time, the error increases at the middle of the training session when audio and visual stimuli become imperceptible, and reaches the error level of the haptics only condition. The transition to the evaluation session causes a significant gap for the visual and audio conditions, but the error finally appears to be approximately at the same level regardless of the training strategy.

For the task completion time, we globally observe a slight decrease during the training session. Subjects appear to be slower in the auditory learning conditions, even when the feedback disappears.

We can quantify the efficiency of the five learning strategies concerning the mastering of the interaction. Figure 7 shows the performances during the evaluation session with respect to the learning strategy group. Statistical analysis exhibits a significant effect (at $\alpha = 0.05$) of the learning strategy on the absolute value of the error (one-way ANOVA: $F_4 = 221$, $p=0.011$). This effect appears to be only due to a slight difference between the *fading out Audio* and *fading out Visual* condition (Post hoc Tukey's test: $p_{fV-fA} = 0.012$)

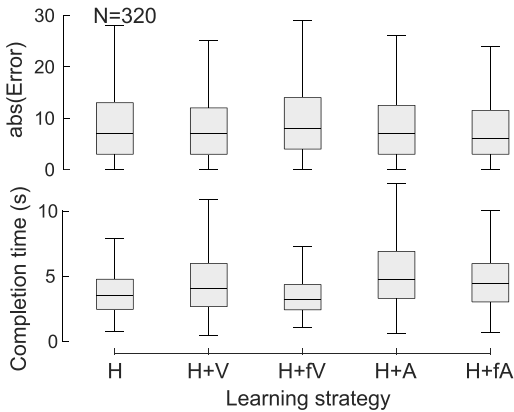


Figure 7: Performances during the evaluation session for the five groups of subjects associated to the five learning strategies.

Learning strategies also have a significant effect (at $\alpha = 0.05$) on the completion time during the evaluation session (one-way ANOVA: $F_4 = 13.66$, $p=5.9 \cdot 10^{-11}$). The post hoc Tukey's test reveals that this effect is due to the *Visual*, *Audio* and *fading out Audio* conditions that lead to a significantly higher completion time.

As the error disparities are low and the p-value is still close to the level of significance, we assume that there are no major differences between the learning strategy groups during the evaluation session in terms of task error and that statistical artifacts could be due to the high subject variability.

Both the learning curves and the boxplot show that the task completion time is longer for conditions with audio feedback. As audio stimuli are based on the sonification of the haptic signal, whose temporal variations depend on the finger velocity, it is possible that subjects adjusted their exploratory motion to optimize the information acquisition from the sound. Remarkably, subjects maintain this slower exploratory motion even when the audio feedback is removed, for the *fading out* condition and for the evaluation.

5.3 Inter-subject variability

We investigated inter-subject variability to better understand the previous results. Figure 8 presents the subjects' performances in a two-dimensional space, with mean error and completion time as dimensions (outlier trials excluded). Intra-subject variability is also displayed through the error bars. The bottom-left corner corresponds to subjects with the best performances, i.e. the lowest error and the fastest completion time. Since subjects adopted various approaches during the task performance, their performances vary greatly. The graph shows large disparities between the subjects, which makes it difficult for a trend in learning strategy to emerge. We can still observe that the subjects with audio learning conditions (in green) are mainly in the upper part of the graph, as they spend more time performing the task.

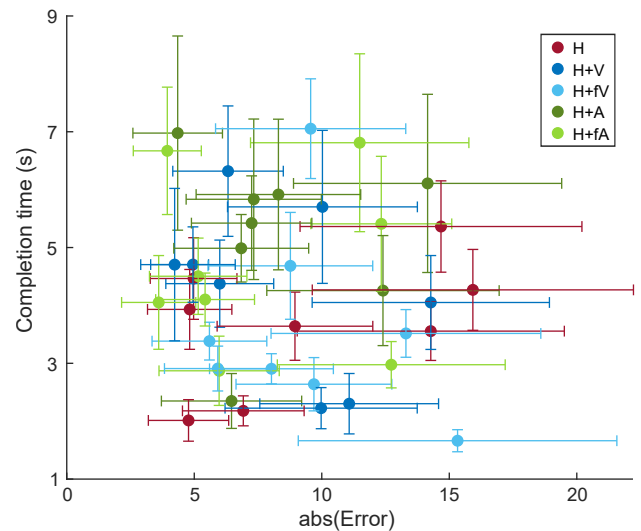


Figure 8: Illustration of the inter-subject variability for the task with haptic feedback only. Each point corresponds to one subject, characterized by its performances: the mean completion time and the mean absolute value of the error on all trials during the evaluation session. Error bars show the standard deviations, which reflect the intra-subject variability. The 5 learning strategies are presented with different colors.

6 DISCUSSION

Participants were able to adjust a setting on a 0 to 100 scale with an error of 8.1%, using a progressive haptic feedback only. In comparison, for the same task with visual feedback in the form of a slider on a screen, the setting error was approximately at 2.2% (mean of the last 100 trials of the H+V condition). On our custom-made interface, such setting errors correspond to finger position shifts of 24.3 mm with haptic feedback and 6.6 mm with vision, both are within the same order of magnitude as the size of the contact made by the fingertip. The results reveal that setting a value on a screen using only haptics leads to degraded results compared to using a screen, but still within an acceptable level of performance. This discrepancy should be taken into account while designing haptic interfaces by adding a margin of error or dead-zones. Alternatively, the progressive haptic feedback interaction without vision can be used in applications that require a low precision, such as window controls. The experiment was limited to reaching only two target values from a lower starting point. However, these targets values were chosen arbitrarily and the gradual haptic feedback does not present any additional cues at these particular locations. In practice, gradual feedback allows the users to reach any target value with the same precision thanks to its construction based on Weber-Fechner Law. Therefore, this interaction provides an absolute adjustment of the setting, whereas conventional binary haptic feedback only provides relative adjustment to change the setting by a certain amount.

Furthermore, across conditions and subjects, the task is performed within an average of 4.1 s using haptic feedback, which is

comparable with the visual feedback condition of 3.5 s. The completion time increases with larger distances, similarly to Fitts' law. However, we found that the relationship between distance and time is linear and not logarithmic, perhaps due to the nature of the interaction, which differs from a pointing task and thereby involves other control mechanisms.

The learning curve during the training sessions with only haptic feedback demonstrates that subjects needed about 35 trials to reach 95% of the final error level, which shows that the interaction is mastered remarkably quickly. The initial trials with only haptic feedback were two times more laborious than the steady state performance and about three to four times longer than with visual feedback, suggesting that the task with only haptic feedback is initially cognitively demanding. However, after even a short training session, the differences in performance vanishes, which is a promising result for enabling eyes-free control of sliders.

We found that the type of training feedback had little effect on the final performance during the evaluation session. However, these results were obtained from 8 subjects by groups. Since the inter-subject variance is large, the absence of a larger effect could be due to a too small sample size. By design, participants were aware of the absence of feedback during the evaluation session before starting the experiment. As a consequence, some of them reported that they had focused on the haptic feedback and paid less attention to the visual or auditory feedback. This might explain why the performances were the same with additional concurrent feedback presented during the whole training session, whereas this type of strategy was reported in the literature to be less effective for retention [35, 38]. Finally, given the relatively low impact of congruent feedback, we can conclude that the terminal feedback, given on a digital display, seems to be the essential factor enabling the retention process.

Since retention after training did not depend on the learning modality, the learning method can be adapted to different contexts and to the users' preferences. Visual feedback would be selected preferentially for its simplicity and rapidity of training, but auditory feedback can complement vision. Auditory feedback still requires more time for learning, perhaps because users are less familiar with this kind of feedback since it is scarcely implemented. Additionally, the learning curves show a plateau after about 40 trials, or four blocks, so in practice the training session could probably be significantly shortened.

Only short-term retention has been studied, with the evaluation performed immediately after the training. Future research will investigate to which extent users can capitalize on their learning over a long period. In addition, since the interaction was learned in laboratory conditions, it would be interesting to contextualize the experiment to real-life scenarios and evaluate the device and the learning procedure in real situations, as in a car cockpit [26] or even in the subway [18]. In these cases, it would also be necessary to quantify the potential decrease in tactile sensitivity due to the mechanical vibrations of the vehicle.

In realistic cases, we cannot expect the visual and auditory feedback to be always present. However, we expect that the current method based on haptic feedback will facilitate the operation of the slider without having to look at it or in a noisy environment. We can imagine a practical scenario in which supplementary visual

and/or auditory feedback (according to the user's preferences and the use case) is presented during the first times of service. With time and practice, users will no longer need the support from these additional modalities and will only rely on their haptic perception. For example, in [11] authors showed that using a gesture based sonified interface was challenging at first, but after training, users preferred it to a conventional touch screen in a driving situation as it distracted them less from monitoring the road.

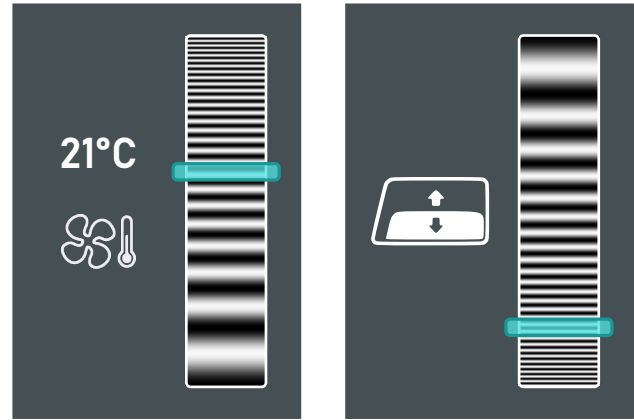


Figure 9: Example of two use cases with graphical display. The gradual haptic feedback illustrated in grey scale enables the user to control the temperature and the opening of a window without vision.

A vertical one-dimensional touchpad was used in these experiments, but the interaction can trivially be extended to two-dimensional touchpads or touchscreens equipped with haptic feedback. Moreover, we used only one type of haptic feedback, a sine wave with a spatial frequency gradient. To recognize the parameters in a complex interface for example, we can imagine other types of haptic stimulations, such as random irregularities or amplitude gradients [9]. As illustrated in Figure 9, the interaction with progressive haptic feedback can be implemented in a wide range of human-machine interactions, such as the setting of the temperature level, the strength of ventilation or the music level, the selection of a radio station, the opening of windows or stores either on a touchpad or also directly on the touchscreen.

7 CONCLUSIONS

We propose a new control device that allows setting a value without looking at it, using a new haptic touchpad. Haptics from the surface is the only source of information describing the current setting value. By feeling a texture that evolves continuously, the control parameters of the interface can be adjusted in an absolute way, a task that until now seemed impossible without vision. This interaction was assessed in a study in which users had to reach two target values in an evaluation session immediately following the training session. After learning, users succeeded in performing the eyes-free task with 8.1% of error and in 4.1 s on average. This performance comes after a short learning period, during which any kind of feedback seems to help improve the skills. This new guidance method which

leverages a continuous mapping of the haptic cues to an abstract value has only marginal degradation of performance compared to the use of visual cues. Providing this feedback on touchscreens can reduce distraction and improve intuitiveness of the interaction.

ACKNOWLEDGMENTS

This work was conducted in the framework of the Openlab Stellantis-AMU “Automotive Motion Lab”. The authors thank Sebastien Denjean, Nicolas Huloux and Laurence Willemet for their thoughtful comments on the experiment and on the manuscript.

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