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Eyes-Free Fingertip Guidance Based on Tactile Cues, an Extension of the Steering Law

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Abstract—The use of a modern human-machine interface involves a large amount of possible interactions. In order to allow users to navigate through a large number of available operations, interface designers often use drop-down menus that offer many options in a constrained area. This kind of menu shows good performance for selecting quickly from a large amount of choices. However, they require a high visual attention which is not always possible for the user. Here, we investigate if one can navigate through paths made of orthogonal tunnels, simulating drop-down menus, relying only on tactile cues on a haptic touchscreen. We found that subjects were able to follow the path with a success rate of $\sim 90\%$ for 1 tunnel which decreased linearly to $\sim 40\%$ for 5 tunnels. Four types of friction-modulated haptic feedback were tested and showed no major differences in terms of success rate. Nevertheless, participants were slightly faster with slipping path feedback. The user trajectories presented robust regularities that could be well described by the steering law model. Hence, we propose a novel definition of path difficulty for non-visual conditions based on path width, length and number of orthogonal tunnels. These findings pave the way toward eyes-free guidance on surface haptic interfaces.

Index Terms—User guidance, Surface haptics, HMI, Steering Law, Eyes-free interaction, Tactile feedback.

I. INTRODUCTION

Human-machine interfaces have evolved to a point where they can provide thousands of functionalities. One common design for navigating through computer interfaces and triggering the right operation on demand is a cascading drop-down menus. These menus provide access to a large number of options within a constrained space.

They show good performance when it is possible to give them visual attention [1]. However, in situations where visual attention is required elsewhere, such as when driving, this interaction is less relevant since it relies mainly on vision. In these cases, mechanical knobs and sliders are usually preferred since they can easily be grabbed and operated without sight [2]. However, they are limited to a single interaction and cannot achieve the versatility and reconfigurability that touchscreens provide.

Haptic surfaces are a kind of human-machine interface used to restore the tangibility of touchscreens interfaces. In order to provide information through the tactile sensory channel, they produce haptic stimuli directly onto the user's fingertip

by modulating the friction between the fingertip and the interface. The friction can be controlled using either ultrasonic levitation [3]–[5] or electrovibration [6], [7]. Through friction changes, these haptic surfaces can produce the tactile illusion of feeling shapes and textures [8]–[10]. Haptic touchscreens have already demonstrated their potential to assist users in operating interface without vision [11], [12].

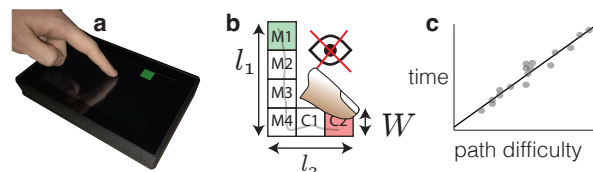


Fig. 1. a. An example of a subject navigating through a path on the haptic touchscreen. b. Navigation through drop-down menus could be modeled as a succession of orthogonal tunnels of length l and width W . The tunnels are purely haptic, only the green start box appears on the screen. c. The mean movement time for each path appears as proportional to a difficulty index composed of the number of tunnels and the total length of the path. This is similar to a steering law.

To evaluate the performance of a human-machine interface, actions such as selecting an icon or navigating through a menu are often modeled by so-called Fitt's tasks [13], [14]. Fitt's law accurately predicts, for a given interface, the time required to move a pointer to a target area depending on how far it is and its dimensions. This allows one to compare and rank different kinds of interfaces according to how fast such a task can be completed.

Thus, it has already been shown that haptic feedback enhances the performance in Fitt's tasks [15]–[19]. Furthermore, it is possible to do such tasks relying only on haptic feedback and not on sight [20].

To some extent, drop-down menus could be seen as a succession of Fitt's tasks, where each target is alternately on the same horizontal or vertical axis as the previous one. However, to properly use a drop-down menu, the user must ensure that the pointer stays within a path. If the user strays out, an unwanted sub-menu might open or even cause the whole menu to close altogether. Therefore, drop-down menus are better modeled as steering tasks [21]. In this model, each part of the menu is a straight tunnel that the pointer must

stay within. The steering law, an analog to Fitt’s law, predicts that the time to go through a tunnel depends on its length and width. In classical drop-down computer menus, where vertical paths are much larger than horizontal ones, Ahlström has refined the analysis by considering vertical and horizontal motions separately [22]. The latest is not explored here, since we simplified menus by taking horizontal and vertical paths at the same width.

Since most of the steering law theory relies on visual appreciation of the path to follow, we may wonder how this framework can be applied to steering tasks performed in eyes-free conditions.

In non-visual conditions and for curved paths, previous work noticed that the steering law was not relevant because of the discontinuities and noise in the trajectories [23].

However, we do think that constrained exploration in orthogonal paths, such as drop-down menus, are a special case of guidance, and is more likely to suit a mathematical framework such the steering law, as presented in Fig. 1b and c.

Here, we investigate the possibility of guiding the user’s fingertip onto a touchscreen within constrained invisible paths composed of orthogonal tunnels, only relating on haptic feedback produced by an ultrasonic friction modulated device, Fig. 1a.

We observed that the average task completion time linearly increases with the path difficulty as defined from our adapted version of the steering law in the non-visual context, Fig. 1c.

We also investigate whether the type of haptic feedback presented to the subjects would influence task performance, both in terms of success rate and time to completion. Within the four haptic conditions, we observed that people have their own preferences. Nevertheless, we show that a textured stimuli produced on path seems to have an overall slightly higher performance for guiding one’s fingertip.

We therefore designed an experiment to:

- demonstrate that a user can follow a path just with tactile cues alone;
- measure the influence of the type of haptic feedback on the performance of the task;
- verify if the movement time of the task follows a steering law.

II. TASK DIFFICULTY THEORY

The paths used in the present experiment are constructed as a succession of orthogonal tunnels. We use the framework of Accot and Zhai [21] to study the individual tunnels. They propose to define the index of difficulty (ID) of a straight tunnel as:

$$ID_{\text{tunnel}} = \frac{l}{W \ln(2)} \quad (1)$$

where l is the length of the tunnel and W its width.

Using this definition, they show that the average movement time (MT) to go through a tunnel is robustly predicted by:

$$MT_{\text{tunnel}} = a + b \times ID_{\text{tunnel}} \quad (2)$$

where a and b are empirically determined constants. In the present experiment, the task of following the entire path can be decomposed into successive tasks of following straight tunnels. An example of a path composed of three tunnels is shown in Figure 2. The global movement time of the path can be estimated as the addition of the movement time of each tunnel:

$$\begin{aligned} MT_{\text{path}} &= MT_{\text{tun1}} + MT_{\text{tun2}} + \dots + MT_{\text{tunN}} \\ &= a + bID_{\text{tun1}} + a + bID_{\text{tun2}} \\ &\quad + \dots + a + bID_{\text{tunN}} \end{aligned} \quad (3)$$

Since the empirical coefficients a and b are not affected by the parameters of each tunnel, this equation can be rewritten as:

$$MT_{\text{path}} = N \times a + b \frac{l_1 + l_2 + \dots + l_N}{W} = N \times a + b \frac{L}{W} \quad (4)$$

where N is the number of straight tunnels and l_1, l_2, \dots, l_N are the lengths of the corresponding tunnels that compose the total path of length $L = l_1 + l_2 + \dots + l_N$.

Finally, we rewrite equation 4 as:

$$MT_{\text{path}} = a \left(N + \frac{b}{a} \times \frac{L}{W} \right) = a \times ID_{\text{path}} \quad (5)$$

This is a formulation of the index of difficulty of the path (ID_{path}) expressed as a function of the path’s length, width and number of tunnels, corrected by an empirically determined coefficient.

In the literature, the steering law was defined for visual tasks [21], [22]. To investigate its generalization to non-visual tasks with haptic feedback, the present experiment aims at measuring the empirical coefficients and verifying that the movement time is indeed linearly correlated to this index of difficulty.

III. MATERIAL AND METHODS

A. Apparatus and stimuli

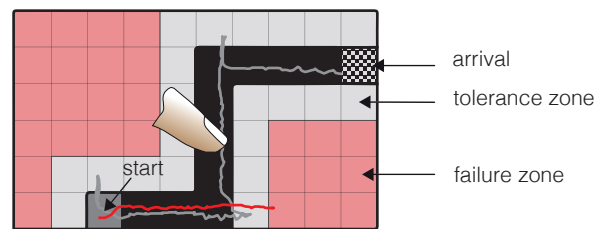


Fig. 2. The experiment featured 20 different paths composed of 1 to 5 tunnels. Paths were built from 15.4 mm squares. During the experiment, only the start was visible and tactile effects were generated on the haptic surface for fingertip guidance. The path (black) always had a different tactile rendering from the rest of the screen. If the fingertip left the gray zone and entered the red zone, the task was failed and the level was stopped. Lines are examples of trajectories for a successful (gray) and a failed (red) trial.

The study was performed with a Xplore Touch haptic surface (Hap2U, Grenoble, France). This device uses ultrasonic levitation to render friction-modulated haptic feedback. It is composed of a 154 × 86 mm capacitive touchscreen controlled by a Raspberry Pi 4. The experiment was conducted with a

Python script that renders the graphical interface and controls haptic feedback using an API developed by the Hap2U company.

We considered two parameters that have two possible values in the design of haptic feedback, totaling four different tactile stimuli. The first parameter determines where the stimuli is produced: on the path or off the path (*affirmative*, and *negative* information). The second parameter determines the nature of the haptic stimuli being produced (slippage or texture).

Figure 2 represents a typical path with haptic zones. When the stimuli is rendered on the black path it is affirmative information, whereas when it is rendered on the gray zone, it is negative information.

Two types of haptic feedback are generated. They are carried by a $\simeq 40$ kHz excitation signal that make the plate vibrates in a resonant mode. The first one, which is called *slippage*, consist in a constant low friction stimulus generated by actuating the haptic surface at its maximum power which correspond to a maximum of $\simeq 2 \mu\text{m}$ of vibration amplitude. This stimuli produces sudden friction changes at the path borders. The second haptic signal, which is called *texture*, is a haptic stimulus rendered by modulating the ultrasonic vibration by a sine wave at a spatial frequency of 2.9 mm (20 pixels) of amplitude $\simeq 2 \mu\text{m}$. Hence, the experiment features four types of haptic feedback: *texture* on the path or in the tolerance zone, *slippage* on the path or in the tolerance zone.

B. Task and experiment design

At each trial, participants were asked to place their finger on the starting point and to follow the haptic path, with a constant touch, as quickly as possible until they reached the end. A trial was considered a failure as soon as the user's finger moved far enough away from the path that it left the tolerance zone. It was considered a success if the participant's finger reaches the end of the path. At the end of each trial, the participant is informed of their success or failure, then the next trial began. Participants were aware of the failure condition of the task and were asked to avoid failing.

Figure 3 shows the 20 different paths used in the experiment. The paths were made of 1 to 5 orthogonal tunnels with length varying from $[6 - 20] \times 15.4$ mm (100 pixels). Since a typical fingertip's diameter varies between 16 and 20 mm, the chosen width ensures that a user can navigate the path [24]. Each path has been explored with 4 types of haptic feedback, for a total $20 \times 4 = 80$ trials per participant. The paths were presented randomly as blocks of haptic conditions. The order of the blocks was randomized across participants.

Each block started with a learning session of 3 paths, each composed of 3 straight tunnels. The participants were asked to first complete the task while the paths were displayed visually, then again using only haptic feedback. During these 6 trial runs, there was no possible failure; participants could move their finger anywhere on the surface without consequence.

There was no time limit and participants could take as long as they wanted on each trial. On average, it took about 30 minutes for a participant to complete the experiment.

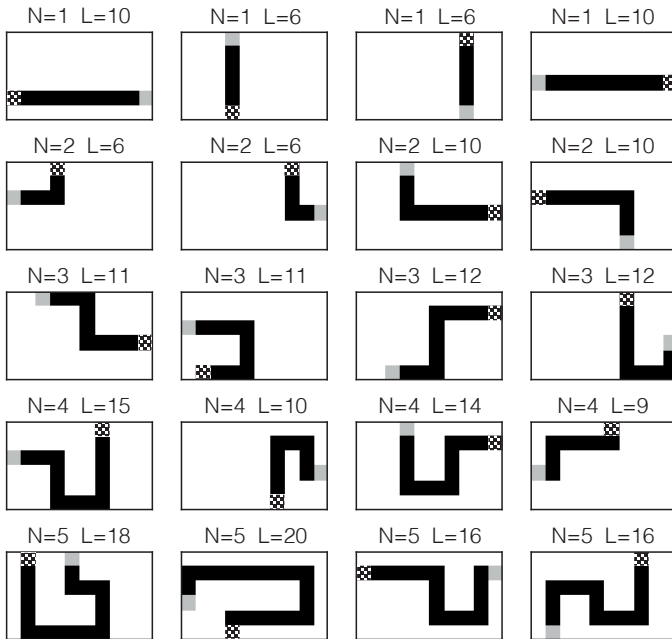


Fig. 3. Representation of the 20 paths used in the experiment, with the number of tunnels N and its associated length L . The length is here presented in the number of squares and can be multiplied by 15.4 mm to get a conventional unit. The starting zone is in light gray and the arrival in check pattern.

C. Participants

21 volunteers, 8 females and 13 males, 19 right-handed and 2 left-handed, ranging from 18 to 54 years old (mean 33.9) took part in the experiment after giving their informed consent. They were naive to the aims of the study. Before the experiment, subjects washed and dried their hands and the touchscreen was cleaned with isopropyl alcohol. Some candidates did not feel the haptic feedback well and were not able to resolve the task. They did not perform the experiment and therefore are not counted here.

D. Metrics measurement

For each trial, the device recorded the finger position with respect to time. A trial was considered successful if the user reached the target without their finger leaving the tolerance zone. We can then compute as a first comparison metric the task outcome: success or failure. As a second metric, we examined the movement time MT , defined as the duration between the beginning of the trial, *i.e.* when the participant placed their finger on the starting zone, and the end of the trial when they reached the target zone (arrival).

IV. RESULTS

A. Success Rate

Overall, the participants successfully completed the task 55 percent of the times, with large differences between subjects (from 24 to 95% of success rate).

We found that the mean success rate for a given path was highly related to the number of straight tunnels of the path. Regardless of the haptic feedback condition, a chi-squared test of task outcome contingency tables proved a significant influence (at $\alpha = 0.05$) of the path's number of tunnels N on the success or failure of the task ($\chi^2(3)=12.7$, $p = 0.005$).

Figure 4.a. shows that the success rate decreases as the number of tunnels increases (and therefore the number of direction change). A linear regression ($F(3)=14.4$, $p=0.03$, $R^2=0.83$) confirmed this trend. In contrast, the success rate was poorly predicted by the length of the path ($R^2 = 0.45$).

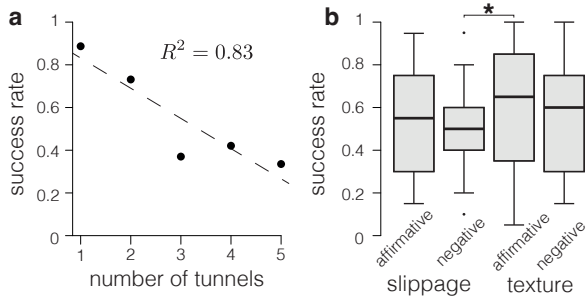


Fig. 4. **a.** Influence of the number of straight tunnels on the success rate over all trials of all conditions and its linear regression ($R^2 = 0.83$). **b.** Comparison of the success rate per subject ($N=21$ subject for each condition) between the four types of haptic feedback.

The mean success rate was also calculated for each type of haptic feedback and for each participant, so as to investigate the impact of the type of haptic feedback, as presented in Figure 4.b.

A Friedman non-parametric test showed a significant effect of the haptic feedback condition on the success rate ($\chi^2(3)=9.13$, $p=0.03$) and Nemenyi post-hoc tests revealed that this effect was due to a significant difference between the *negative slippage* and *affirmative texture* haptic feedback.

B. Movement time

The task completion time was analyzed by considering only the successful trials. Statistical analyses showed that the movement time was significantly impacted by the size of the path L (One-way ANOVA: $F(9,864)=66.3$, $p<0.001$,) and its number of tunnels N (One-way ANOVA: $F(4,869)=137.8$, $p<0.001$).

A multiple linear regression of the movement time MT on both the path's length L and its number of tunnels N allowed us to determine values for the coefficients of equation (4): $a = 1.97$ and $b = 0.83$, with an intercept value of $c = 0.79$ ($R^2 = 0.95$).

Moreover, as shown in Figure 5.b, the movement time was significantly lower for the *affirmative slippage* haptic feedback

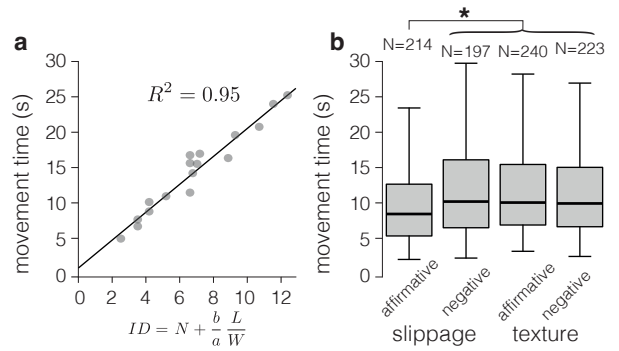


Fig. 5. **a.** Result of the steering law adaptation: the mean movement time MT is plotted as a function of the index of difficulty ID (function of the path length L and number of tunnels N). The movement time was averaged for each path. The linear regression is plotted as a continuous line. **b.** Comparison of the movement time between the four types of haptic feedback on all succeeded trials. Boxplots are displayed without outlier trials for clarity.

compared to the others (One-way ANOVA: $F(3,870)=4.6$, $p=0.003$, and Tuckey post-hoc: p_{AS-NS} , p_{AS-AT} and $p_{AS-NT} < 0.02$).

V. DISCUSSION

A. Performance of the eyes-free interaction

The results demonstrate that users are able to follow a path on a haptic touchscreen just by feeling tactile cues alone. Yet the overall success rate was not as high as it could be with vision [21]. However, with regard to the path difficulty, our results show good consistency with the predictions from the steering law, which is originally used for visual interfaces [25], [26]. There were also large inter-individual discrepancies in success rate. We hypothesized that this was due to differences in exploration strategy, with some participants favoring speed over accuracy. In addition, some subjects reported that they did not always feel the haptic feedback well. Friction modulation perception is indeed impacted by the participant's tactile acuity and by the mechanical properties of their finger, some of which can vary during the experiment (such as moisture). Future work could improve the robustness of the haptic feedback. Furthermore, the learning session before the trials was done rather quickly: it was sufficiently long for the participants to understand the task but not long enough for them to master it. Since the vast majority of human-computer interfaces rely on sight and audition to convey information, interactions with a haptic interface likely require a period of adaptation for users [12]. Figure 4.a showed that the success rate was lower than expected for paths with 3 tunnels. We suppose that this was due to the fact that 3 out of the 4 paths with 3 tunnels had a first tunnel that was parallel to the screen border. Since participants tended to start their movement perpendicularly to the screen, this appeared to be a significant cause of error.

B. Influence of the type of haptic feedback

The protocol compared four types of haptic feedback: affirmative or negative feedback, effected with either constant friction levels (*slippage*) or with friction modulated textures

(texture). The experiment revealed only small differences in performance across the four haptic conditions, which is consistent with the literature [26]. Nevertheless, the affirmative slippage feedback had the lowest average completion time. Further analysis showed that participants moved their finger significantly faster in this condition. We hypothesized that participants were more confident with this feedback since their finger was slowed down when leaving the track due to the sudden increase in friction. The latest is the major motivation for the use of an ultrasonic vibration device rather than vibrotactile stimuli. However, the results show that a similar task could be succeeded with vibro-tactile stimuli. Since the task was possible with all four haptic feedback conditions, complex interfaces could combine different types of haptic feedback to also inform the user about their position in the menu. Furthermore, in this paper, we tested only categorical feedback (affirmative or negative), but it could be interesting to design continuous feedback, such as gradients [27] to study how the performance can be further improved.

C. Adaptation of the steering law to non-visual condition

Previous work conducted in non-visual condition hypothesize that in such conditions movement could not be predicted by a steering law [23]. However, in this study only 2 paths have been tested, hence only two path difficulties have been proposed which could not verify the following of a steering law.

From our experiment's results, the movement time appears to be well predicted by the theoretical equation 4. This is comforted from the linear regression, of equation $aID_{path} + c$, with a R^2 value and a negligible intercept value ($c/\text{mean}(MT) = 0.076$).

Our result provides an empiric definition of an index of difficulty adapted to the steering task through a succession of orthogonal tunnels with haptic feedback. One limitation of the study is that the width of the path was the same for every condition. Therefore, we could not investigate its effect on the movement time and check its role in the equation 5.

The definition of the index of difficulty that we propose here could be useful for the design of future human-computer interfaces based on haptic touchscreen to evaluate their usability and mental demand.

VI. CONCLUSION

Navigating a drop-down menu is akin to guiding a pointer through a constrained path. In fact, failure to stay within the path may lead the user to pick an unwanted option or to close the menu altogether. Therefore, to test whether haptic feedback can be used to design menus that are usable even in vision-less settings, we investigated how participants fared at navigating a series of orthogonal tunnels in eyes-free conditions.

We found that, overall, participants did succeed at completing the task with no visual information, providing evidence for the viability of vision-less haptic interfaces.

We observed that the success rate of the task depended on the number of tunnels in the path. This information is

valuable and should be taken into account when designing haptic menus. It is also worth noting that affirmative slippage feedback allowed for slightly faster task completion than the three other types of feedback.

Finally, we showed that the time to successfully complete a task follows a steering law model. We first defined a task difficulty index theoretically by adapting the original definition of Accot and Zhai to our non-visual condition, then found it matched our experimental results very well. This result would help to optimize the design of haptic interfaces.

Taken together, these findings pave the way toward haptic design for human-machine interaction where visual attention cannot be allocated to the task. Moreover, it could help visually impaired people to interact with touchscreens.

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