Viscous Damping Displayed by Surface Haptics Improves Touchscreen Interactions

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Abstract. Virtual targets on touchscreens (e.g., icons, slide bars, etc.) are notoriously challenging to reach without vision. The performance of the interaction can fortunately be improved by surface haptics, using friction modulation. However, most methods use position-dependent rendering, which forces users to be aware of the target choice. Instead, we propose using tactile feedback dependent on users' speed, providing a viscous feeling. In this study, we compared three viscous damping conditions: *positive damping*, *negative damping*, and *variable damping* (viscosity was high during slow movements and low during fast movements), against a baseline condition with no tactile feedback. These viscous fields are created by changing net lateral forces based on velocity. Results indicate that, during the initial phase of movement when the finger approaches the target, various viscous feedback has an insignificant impact on targeting trajectories and movement velocity. However, positive damping and variable damping significantly influence behavior during the selection phase by reducing oscillation around the target and completion time. Questionnaire responses suggest user preference for viscous conditions and disapproval of negative viscous forces. This study provides insights into the role of viscous resistance in touchscreen interactions.

Keywords: surface haptics · viscous forces · pointing tasks

1 Introduction

Because of the lack of tactile cues, users interacting with touchscreens and touchpads have to interact using only visual cues. The need for visual attention can be dangerous in situations such as driving or walking. While some manufacturers are reverting back to physical buttons, they are also losing the flexibility that touchscreens provide. Programmable tactile feedback, where feedback is provided to the user's bare finger, circumvents all these limits and reduces the need for visual attention. Moreover, the feedback enhances the performance of the interaction and improves the overall user experience. The standard approach to implement programmable tactile feedback, commonly found in consumer electronics, uses vibrotactile feedback to inform users with vibrations [13]. While

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effective at signaling the user, vibrotactile feedback only provides transient or periodic stimulation. In contrast, friction modulation offers finer and continuous stimuli providing a natural physical rendering of a target. It has been shown that a simple binary friction profile reduces pointing task completion time by providing more intuitive guidance to users [4,16,23].

However, all existing methods that employ position-based feedback require knowledge of the target location and, consequently, must predict the user's intention in selecting their target. The position-based approach can be effective when the interface has only a few targets but may be impractical when localized targets do not exist. To facilitate interaction across complex interfaces, we need to implement a target-independent rendering strategy, for example, velocity-dependent forces that feel similar to viscous elements to guide the user on the surface.

Pointing tasks, where the finger reaches a target on the screen, are fundamental in human-computer interaction. Fitts demonstrated that the time taken to reach a target during these pointing tasks depends on its distance and width [8,9]. The kinematics are governed by the principle of minimum variance control [12,20,21], suggesting that users minimize target variance by slowing down when approaching a target. The velocity profile forms a bell shape, dividing into two phases: an approaching phase, resembling a ballistic movement with minimal sensory feedback [5,17], and a subsequent slower adjustment phase to pinpoint the exact location using continuous sensory feedback.

Therefore, we postulate that task completion time can be reduced by modulating feedback along these phases. This translates to accelerating the ballistic movement for a quicker approach and slowing down the adjustment phase for

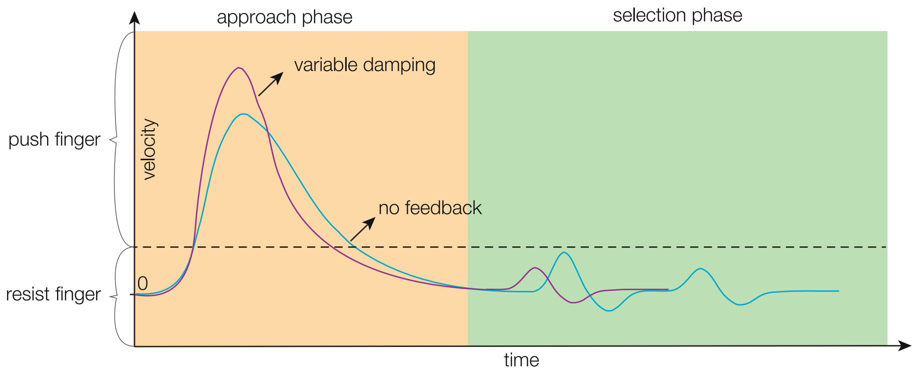

Fig. 1. Typical velocity profiles observed during a pointing task. The cyan curve represents a typical velocity profile without tactile feedback, where the finger moves back and forth when selecting a target. The purple curve illustrates the proposed approach that varies damping. We hypothesize that, during the approach to the target, low viscosity (or even negative damping) can accelerate finger movement, while during the target selection, high viscous viscosity helps locate the target with fewer back-and-forth movements.

finer control, as illustrated in Fig. 1. We implemented this strategy by changing the damping coefficients as a function of the user's velocity. For example, we can display negative damping at high speeds to increase speed and positive damping at low speeds to dampen the approach. We expect that this feedback provides better performance with a shorter time to completion compared to scenarios without tactile feedback.

Viscous-based assistance has been implemented in the past using force feedback. In contrast to surface haptics, users interact with force feedback devices through a handle rather than their bare fingers. Despite these differences, the findings offer insights into expected behavior. Notably, it has been observed that adding constant static friction leads to a decrease in reaching times and improves accuracy when moving low-mass objects [1,6,19]. This improvement is attributed to friction forces decelerating and filtering out jittery movements. Keemink et al. demonstrated that both constant damping and position-dependent damping reduce movement time and increase endpoint accuracy [15]. These findings suggest that viscous damping in force feedback operations is beneficial to human operators. The impact of such forces on bare fingertip interactions remains unexplored, in part due to the lack of a surface haptic device capable of providing the desired lateral force.

In this paper, we investigated the effects of variable viscous damping on users' targeting strategies using a novel surface haptic device called Ultraloop [3]. This device generates lateral forces based on the user's velocity. We compared users' performance when reaching targets when presented with a positive damping, a velocity-dependent damping, a negative damping, and a control condition without any damping. We found that viscous conditions do not significantly affect the movement trajectories during the approach phase but notably decrease the back-and-forth movements during the selection phase.

2 Methods

2.1 Setup

In this work, we render viscous environments by changing the net lateral forces, with a consistent reduced friction, as a function of velocity. The lateral forces are produced by active surface haptic devices that use ultrasonic traveling waves, e.g. [2,3,10,11]. Here, we use a haptic touchpad, called the Ultraloop, which can deliver active lateral forces on a relatively large surface of $140 \times 30\ mm^2$. It has an aluminum ring-shaped cavity in which two degenerate resonant standing wave modes are excited at approximately 40 kHz with a 90° phase shift. These standing waves superimpose into either a counter-clockwise (when the phase is 90°) or a clockwise (when the phase is -90°) traveling wave that propagates around the ring. The traveling wave interacts with the skin and produces a net lateral force that can push or pull fingertips. The direction and magnitude of the force can be modulated by varying the amplitude and phase shift of these standing waves. To create lateral forces as a function of velocity, we used a Teensy 3.6 microcontroller to program the phase of two driving voltages in response to

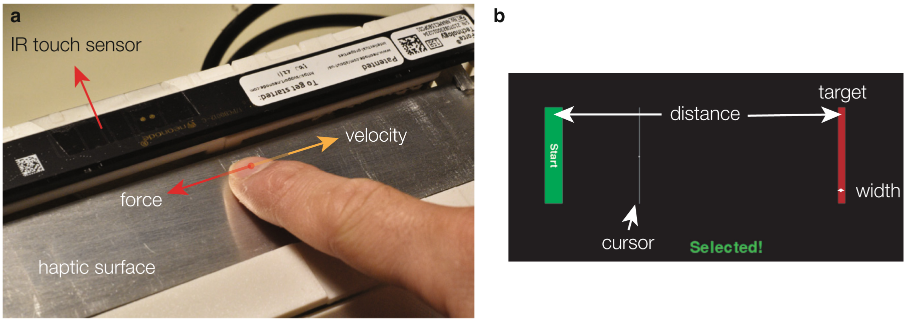

Fig. 2. **a**, Experimental setup: Participants slide their index finger on the touch surface of the Ultraloop while experiencing lateral forces generated as a function of the measured velocity. **b**, Graphical user interface displaying visuals for a one-dimensional reciprocal targeting task.

finger velocity, derived from the first-order backward difference of the position tracked by an infrared sensor (Neonode, NNAMC1580PCEV) (Fig. 2a).

2.2 Experimental Conditions

In the experiments, participants were asked to reach for a target while being assisted by three different viscous environments or not assisted at all (baseline condition). In the baseline condition, the surface had uniform low friction with no externally applied lateral forces. In the viscous conditions, net lateral forces generated by the Ultraloop were a function of finger movement speed, formulated as $F = -bv$, while the strength of friction reduction remains the same as the baseline condition. We designed three experimental conditions:

1. *Positive damping*: Here, b is a constant positive value, creating a viscous resistance similar to what can be experienced in daily life.
2. *Negative damping*: In this condition, b is a negative value, and the faster the users go the stronger the lateral forces push.
3. *Variable damping*: b varies linearly with velocity, turning negative when the finger moves faster than 0.08 m/s.

Due to the limitations of the Ultraloop, the net forces plateau at approximately 300 mN. Therefore, the damping force cannot increase beyond a certain finger speed. Figure 3 illustrates the proposed damping coefficient and phase shift profiles as a function of finger speed for each condition. It is important to note that the amplitude of ultrasonic vibration remains constant across all feedback conditions to minimize variations in the strength of friction reduction. The phase of the driving signals is the only parameter tuned, based on velocity.

2.3 Protocol and Design

The graphical user interface used for the experiment is shown in Fig. 2b. Participants conducted one-dimensional reciprocal targeting tasks. Twelve successive

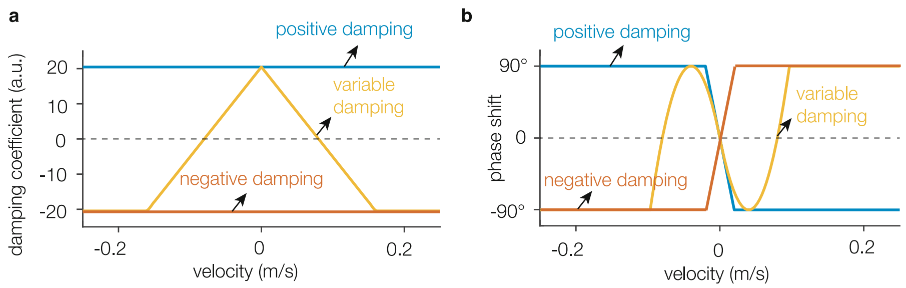

Fig. 3. **a**, Damping coefficients as a function of finger velocity. **b**, Phase shift between the two channels of driving signals. The maximum lateral forces are generated with a phase shift of $\pm 90°$.

tasks with the same target width and viscous condition were grouped together as a block. At the start of each block, they placed their index finger on the active surface of the Ultraloop and slid the cursor to the start area. After holding the cursor in the start area for 0.2 s, the first trial of this block started, and the participant slid the cursor to the target and pressed the "ctrl" key with their non-dominant hand to confirm the acquisition. Next, a new target appeared on the other side of the user interface. Participants were instructed to complete the tasks both quickly and accurately, aiming for a success rate of approximately 96 %. If a participant missed more than one target in a block, a message on the user interface would prompt them to slow down for greater accuracy. Conversely, if they completed one block without any misses, they were encouraged to increase their speed.

We used a repeated within-subject design, with independent variables as viscous environments and target widths. These widths were set at 8, 16, 24, and 32 pixels, equivalent to 0.8, 1.6, 2.4, and 3.2 mm on the touch surface. The target distance is fixed at 7.5 mm. Before experiments, participants spent ten minutes familiarizing themselves with the Ultraloop and the interface.

The experiment consisted of 32 blocks, with each block containing 12 trials with the same target and feedback condition. These 32 blocks were divided into four sessions, each dedicated to one of the viscous conditions. We applied a Latin Square design to counterbalance the presentation order of viscous conditions among participants (Fig. 4). Each session had eight successive blocks, with target widths presented in a descending order, and grouped by the same width. Participants were allowed a one-minute break after each block to rest their hands and fingers. In summary, each participant completed 384 trials, calculated as 4 sessions $\times$ 4 widths $\times$ 2 repeats $\times$ 12 targets.

2.4 Participants

Nine individuals from TU Delft participated in the experiments (seven males, and two females; aged 22–32, average age 25.4). All participants were right-handed, had no tactile impairments, their fingers were free of cuts and calluses,

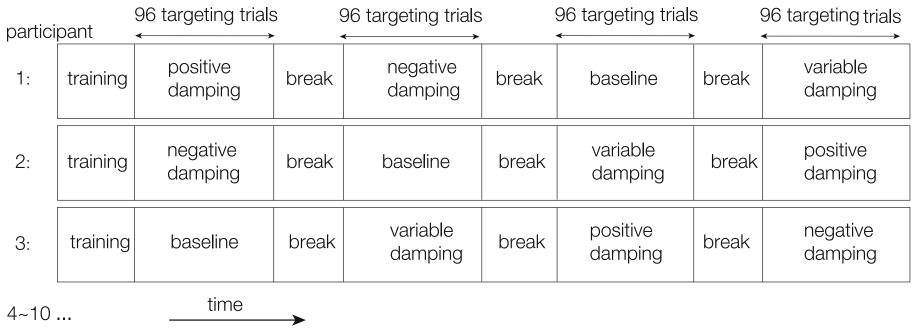

Fig. 4. Experimental procedure overview. Targeting tasks are organized into sessions based on viscous conditions. The sequence in which these conditions are presented to participants is determined by a Latin Square design.

and were unaware of the aim of the study. Every participant provided informed consent before the experiments. The study received ethical approval from the ethics committee of Delft University of Technology, complying with the Declaration of Helsinki.

2.5 Data Processing

The area where participants began the task had a specific width, so we mitigated variations in trajectory timings by aligning the traces to a common reference time point. The velocity profile as a function of position was obtained by interpolating the time-domain position data from each trial. Additionally, we excluded data from the first session of one participant who could not perform movements as fast and accurately as possible, resulting in considerably slower movement compared to the rest of the cohort. In a set of successive trials organized into two blocks of 24 trials, which have the same viscous conditions and target widths, we excluded the first four trials from the first block and the first two trials from the second block to allow for adaptation. The exclusion removed the trial where the learning effect was present, in turn providing focus to the data where the performance was stable.

3 Results

Movement time for each trial is defined as the time between the onset of movement to the selection of a target. A repeated measures ANOVA analysis revealed a significant impact of viscous conditions on the average movement time ($F_{3,21} = 13.392$, $p < 0.001$). Notably, both *variable damping* and *viscous damping* conditions exhibited shorter average movement time (mean = 1.41 s and 1.46 s) compared to the baseline condition (mean = 1.54 s). In contrast, *negative damping* increased the completion time of the pointing task (mean = 1.74 s).

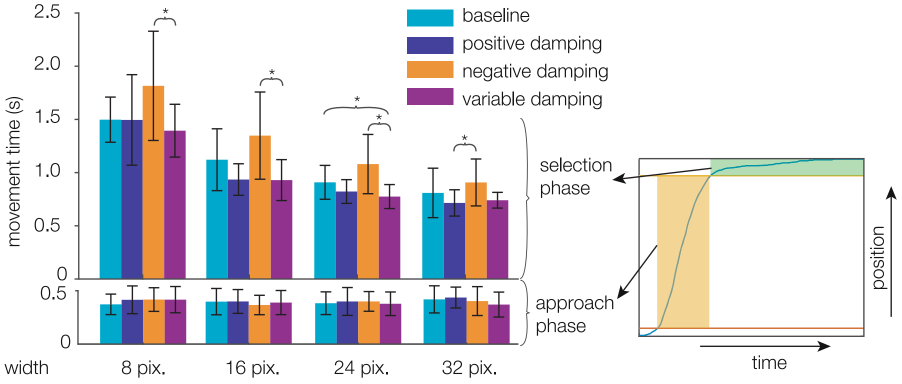

Fig. 5. Mean movement time during the selection phase and approach phase across all target width conditions. Bar charts for these two phases use the same scaling in the y direction. Stars "*" indicate the significance of $p \leq 0.05$. The inset illustrates a typical movement trajectory, with the two phases indicated by the shaded areas.

To explore the potential source for the variance in movement time across viscous conditions, we divided the movement of a trial into two phases: the approach phase and the selection phase. The approach phase spans from the moment the finger exits the start area to when 90% of the target distance is covered. The selection phase comprises the remaining time until task completion. We chose the divide point at 90 % following preliminary observations indicating that the phase before this point exhibits a rapid, monotonous movement towards the target, often described by a bell-shaped velocity profile [17]. Beyond this point, user movements become non-monotonous and involve corrective motions, indicating a shift from rapid approach to precise target alignment.

These phases were represented in the inset of Fig. 5 and statistically analyzed separately to quantify their distinct contributions to task performance. Notably, significant differences in movement times were predominantly observed during the selection phase. Figures. 6 a and b showed that significant differences in movement time were not observed during the approach phase ($F_{3,21}$ = 1.72, p = 0.19), but during the selection phase ($F_{3,21}$ = 12.826, p < 0.001). Specifically, *negative damping* recorded the longest selection time (mean = 1.29 s), while the *variable damping* recorded the shortest (mean = 0.96 s). Further analysis of movement times in different target widths indicated that the primary difference occurred in the selection phase, with minor variations in the ranking of viscous conditions (Fig. 6c).

We further analyzed the averaged movement profiles under the same viscous condition and target width, as depicted in Fig. 7. Across all width conditions, position and velocity profiles showed small differences between viscous conditions, considering notable standard deviations. Additionally, the averaged peak velocities are similar across different viscous conditions. It further suggests that varying viscous resistance does not effectively speed up or slow down user move-

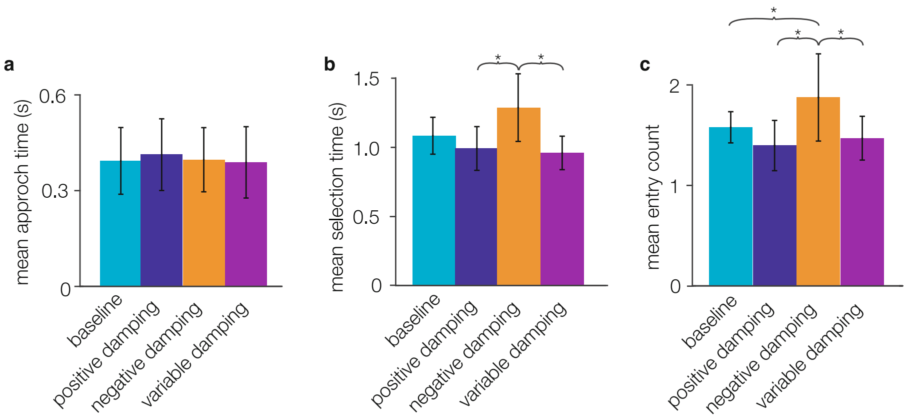

Fig. 6. **a** and **b**, the mean duration during the approach phase and selection phase. **c**, Mean entry count across different viscous conditions. Standard deviations across participants are indicated by error bars. Stars "*" indicate the significance of $p \leq 0.05$.

ment during the approach. Furthermore, averaged velocity versus position profiles during the approach phase also exhibit small deviations from each other for widths of 8, 16, and 24 pixels, yet a relatively larger deviation was observed for a width of 32 pixels. In contrast, the selection phase was notably affected by the viscous conditions. We observed large variations in the number of oscillations around the target and selection duration. The condition *negative damping* significantly increased the average entry count (mean = 1.875), which is the number of times the finger moves into the target area, while both *positive damping* and *variable damping* conditions effectively reduced the number of oscillations around the target (mean = 1.397 and 1.47), compared to the baseline condition (mean = 1.578). Interestingly, despite the opposite viscosity in the *positive damping* and *variable damping* conditions during the approach phase, participants obtained similar entry counts, as indicated by the pairwise post-hoc analyses. It suggests that the selection behavior is primarily influenced by the viscous conditions in the low-speed regime.

After each viscous condition, participants were asked to respond to three questions, with scores ranging from 1 (strongly disagree) to 10 (strongly agree). The questions were as follows: Q1:"I performed well", Q2: "I enjoyed the tactile feedback when interacting with the touchpad", and Q3: "It is easy to hit the target". Responses were collected from eight participants. One participant did not comply with the requirement to complete tasks both quickly and accurately at the first experimental session and was excluded to ensure the reliability of the data. The average scores for all three questions followed the same order across conditions: *positive damping* > *variable damping* > *baseline* > *negative damping*, as displayed in Fig. 8. After completing the experiment, participants were asked to select their most and least preferred conditions. Four out of eight preferred *positive damping*, three *baseline*, and one *variable damping*. In contrast, seven

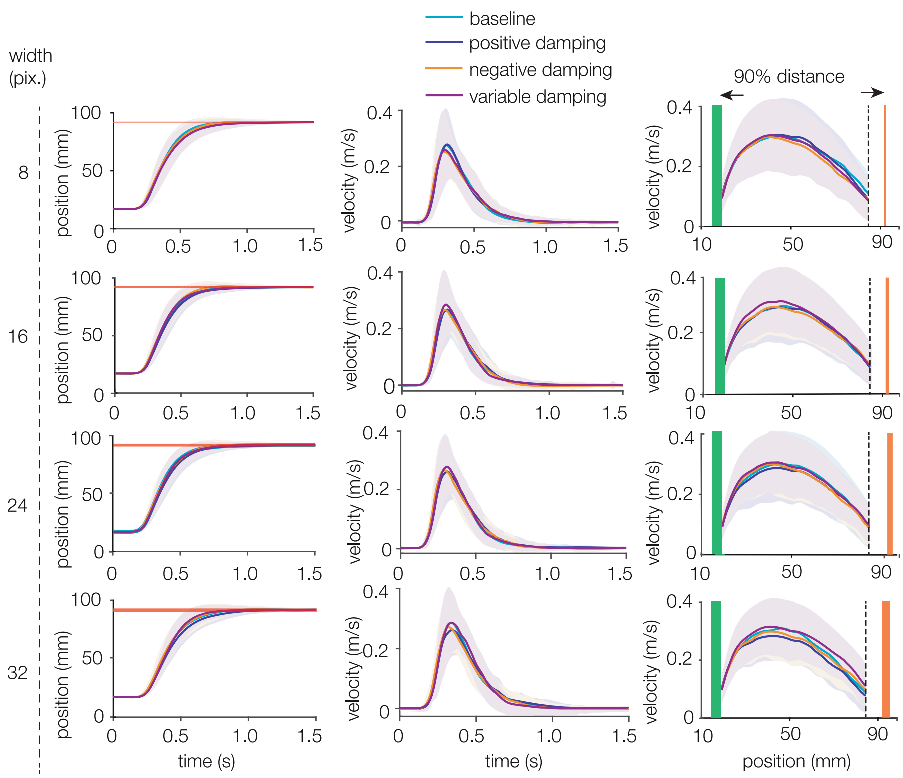

Fig. 7. Averaged movement profiles. Left and middle panels: Averaged movement and velocity profiles of nine participants. Light red bars indicate the targets. Right panels: Averaged velocity as a function of position during the approach phase. Standard deviations are indicated by the shaded areas. (Color figure online)

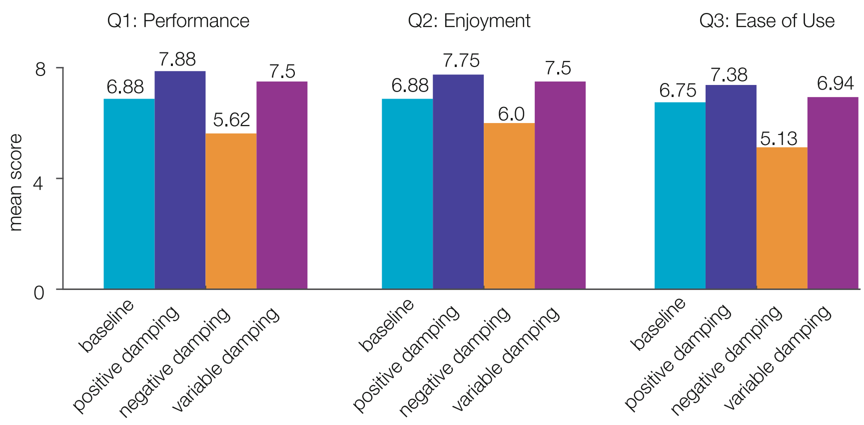

Fig. 8. Mean questionnaire responses, with 10 = strongly agree and 1 = strongly disagree.

out of eight participants chose *negative damping* as the one to not use, with only one choosing *positive damping*.

4 Discussion and Conclusion

We demonstrated a new method to guide users on haptic touchpads and touchscreens. The guidance is created using velocity-dependent forces on the finger, which produce a low damping effect when the finger is moving fast and a high damping effect when it is moving slowly. The user studies indicate that the viscous forces applied to fingertips affect the performance when reaching for a target. The gains in performance are mostly in the later phase of the movement when the user selects the target instead of in the phase when approaching the target. Notably, even when comparing two opposite viscous conditions, i.e., *negative damping* and *variable damping*, their velocity profiles follow similar bell-shaped trajectories, with comparable peak velocities. This observation seems inconsistent with studies using force feedback devices, which reported significant changes in approach trajectories [15]. Two alternative explanations for this inconsistent behavior during the approach phase can be raised.

First, the inconsistency may be attributed to the small variations in the magnitude of the applied force. Hand-operated force feedback devices typically exert forces in an order of 10 N, which are sufficient to impact the limb dynamics. In comparison, the Ultraloop produces much smaller net lateral forces, approximately 0.2 N. The interaction forces at the fingertip —the combination of net lateral force and sliding friction— may differ by a maximum of 0.4 N across different feedback conditions. This variation is notable between *negative damping* and *positive damping*, which produce net tangential forces of opposite signs, with sliding friction consistently opposing movement. These small variations in interaction forces do not significantly accelerate or decelerate finger movement. For instance, in *negative damping*, the forward forces are neutralized by friction forces, possibly leading to resistive interaction forces [10]. The movement during the approach phase likely follows a feedforward behavior, unimpeded by the level of resistance generated by the device.

Second, the short interaction distance in our study was only 7.5 cm, ensuring that participants consistently had a clear visual target throughout the movement. The distance is notably shorter than similar experiments using force feedback devices, such as the 23 cm mentioned in [15]. The salience of the visual cue likely led to a dominance of visual stimuli over haptic stimuli. It is well accepted under the multisensory integration framework that when visual information has a minimal variance, it becomes the primary component of the perceived stimuli. We hypothesize that in this task, participants primarily relied on visual cues, which provided consistent positional feedback. By contrast, the velocity-dependent haptic feedback, which in principle does not infer the target location, played a lesser role. This visual dominance likely explains why variations in viscous damping had minimal impact on the trajectories during the approach phase. This hypothesis is in line with a study by Levesque et al. [16], where the authors report no significant difference in movement speed when using constant low or constant high friction conditions.

Conversely, in the selection phase, where the finger is approaching the target, positive damping gives an advantage to the user for positioning at the right location. We measure the advantage by the reduced oscillations around the target and shorter selection times. The observations align with findings from force feedback device studies [14], where the authors attributed this benefit to haptic damping forces mitigating motor noise during positioning. The positive damping, which creates an energy-dissipative environment, helps dampen unintentional small movements of the user's finger. Our experiments with negative damping show that this effect reverses when the environment is generating energy, creating more oscillations and longer selection times. In addition, participants also described it as the "most challenging," with "unpredictable" movement.

The results regarding active surface haptics can be compared to previous studies that use passive surface haptics with friction modulation. With friction modulation, the target is represented with a low or high friction part, and everything outside is high or low friction, respectively. In both conditions, the friction pattern provides a distinct sensation upon touching the virtual target, and the additional tactile feedback can effectively reduce the need for visual attention. However, the discontinuity in resistance may not be preferred by users [16], especially if it conflicts with other feedback channels or tasks. In contrast, creating viscous damping environments using ultrasonic traveling waves induced active force does not involve a discontinuity in friction or lateral force, which assists in targeting continuously. We believe it improves the movement by attenuating motor noise during the precision epoch of the movement. This feedback scheme smoothly updates the lateral forces, and as a consequence, feels continuous, free from irregularities, and does not interfere with the visual channel. Therefore, it can be an effective complement to the screen in visual-dominant tasks or shared control tasks.

In conclusion, our investigation focused on the effects of viscous forces using active lateral force feedback in touch interactions. Results reveal that viscous forces do not significantly change targeting strategies during the approach to the target but help in positioning toward the target. However, it should be noted that the insights were conducted with only nine participants, which may potentially affect the generalizability of our findings and an improvement could involve a larger participant pool. Moreover, future work could exploit the potential benefits of viscous damping in tasks where moving targets are tracked. With the right design, viscous damping environments may enhance these dynamic tasks that involve frequent acceleration and deceleration [7,18]. Another avenue is to explore how humans adapt to viscous environments created through pure friction modulation. This setting may yield different observations, as humans can perceive friction change before sliding occurs [22].

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