Surfpad: Riding Towards Targets on a Squeeze Film Effect

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ABSTRACT
We present *Surfpad*, a pointing facilitation technique that does not decrease target distance or increase target width in either control or display space. This new technique operates instead in the tactile domain by taking advantage of the ability to alter a touchpad's coefficient of friction by means of a squeeze film effect. We report on three experiments comparing *Surfpad* to the *Semantic Pointing* technique and constant control-display gain with and without distractor targets. Our results clearly show the limits of traditional target-aware control-display gain adaptation in the latter case, and the benefits of our tactile approach in both cases. *Surfpad* leads to a performance improvement close to 9% compared to unassisted pointing at small targets with no distractor. It is also robust to high distractor densities, keeping an average performance improvement of nearly 10% while *Semantic Pointing* can degrade up to 100%. Our results also suggest the performance improvement is caused by tactile information feedback rather than mechanical causes, and that the feedback is more effective when friction is increased on targets using a simple step function.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User interfaces - Graphical user interfaces.

General Terms
Design, Performance, Experimentation, Human Factors

Author Keywords
Pointing facilitation, target-aware, control-display gain adaptation, squeeze film effect

INTRODUCTION
Pointing is a fundamental task of modern human computer interfaces and has been extensively studied by the HCI research community. Fitts' law has proven to be one of the most robust and widely adopted models in this area [29]. It expresses the movement time to acquire a target of width W at a distance D as a linear function of the index of difficulty $ID = \log_2(\frac{D}{W} + 1)$.

Numerous techniques have been proposed that attempt to beat Fitts' law, i.e. to make virtual pointing easier than it is in the physical world [5]. Most of these techniques attempt to decrease D, to increase W, or both. Most of them are also inherently target-aware [34]: they take advantage of some knowledge about the size and position of the targets and sometimes modify them. In cases where pointing involves the indirect control of a visual cursor, some techniques operate by dynamically adapting the control-display gain $CDgain = V_{\text{cursor}}/V_{\text{device}}$ [12]. Other techniques supplement the visual display with auditory or haptic feedback. Yet despite their demonstrated efficiency in simple configurations, most target-aware pointing techniques are difficult to use in practice. One of the key problems that affects them in real-life situations is the potential interferences caused by intervening targets on the way to the primary one (distractors), a problem that is still largely understudied.

In this paper, we present *Surfpad*, a pointing facilitation technique that does not decrease D or increase W in either control or display space. This new technique operates instead in the tactile domain by taking advantage of the ability to alter the coefficient of friction of a particular touchpad, the STIMTAC [9], by means of a squeeze film effect (Figure 1). We report on three experiments comparing *Surfpad* to the *Semantic Pointing* technique [10] and constant control-display gain with and without distractor targets. Our results clearly show the limits of traditional target-aware CD gain adaptation in the latter case, and the benefits of our tactile approach in both cases. Our results also suggest the performance improvement is caused by tactile information feedback rather than mechanical causes, and that the feedback is more effective when friction is increased on targets using a simple step function.

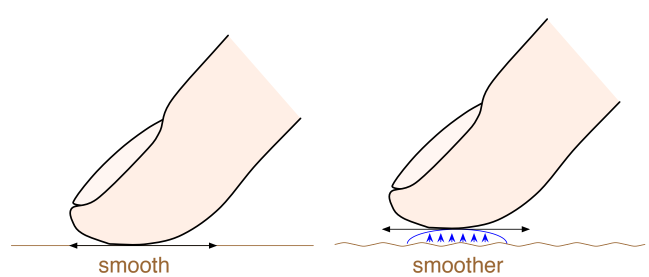

Figure 1. The squeeze film effect: controlled vibration of a surface creates an air film which reduces its coefficient of friction.

The paper is organized as follows. After reviewing related work on pointing facilitation techniques and haptic feedback, we describe the STIMTAC device and our *Surfpad* technique. We then describe our three experiments. We conclude with some directions for future work.

RELATED WORK

A detailed review of pointing facilitation techniques can be found in [5]. As explained, most of these techniques are target-aware and involve the reduction of target distance, the increase of target width, or both. In what follows, we briefly discuss the most relevant examples, focusing on the use of a haptic modality and the impact of distractors.

Reducing D and Increasing W

Different methods have been proposed to reduce target distance. *Drag-and-pop* [7], for example, temporarily brings potential targets closer to the pointer. Other techniques use endpoint prediction to make the cursor automatically jump over empty spaces and potential distractors [19, 4]. The *ninja cursors* [25] reduce D in yet another way by attaching multiple cursors to the same device and using knowledge about the targets to resolve pointing ambiguities.

Different methods have also been proposed to increase target width. *Expanding targets* [27], for example, dynamically grow to provide a larger area to interact with at the focus of attention. Expansion usually occurs in visual space, but sometimes also in control space (more on this below). Research has also shown that the W term of Fitts' law can apply to the width of the cursor, rather than that of the target, which led to the design of different *area cursors* [23, 35, 18].

A problem with the above techniques is that they are often visually distracting because of the displacement, growing or shrinking of objects. Other techniques have been proposed that preserve the display by operating only in control space. Described as *semantic pointing* [10] or using a stickiness or force field metaphor, these control space techniques operate by adapting the CD gain [35, 14, 10] or warping the cursor [31, 14, 13, 1, 21]. The CD gain is typically reduced when the cursor is over targets or approaching them, thereby expanding them in control space. Warping the cursor additionally supports trajectory adjustments in any direction.

A particular case of CD gain adaptation is described in [24], where it is not used to reduce D or increase W but to create a "cursor-catching effect". By requiring more movement effort to leave than to enter the target centre without increasing the total amount of effort to enter and leave the target area, the proposed *dynamic cursor gain* preserves the pointing task's index of difficulty. CD gain adaptation can be seen as a feedback mechanism in this context, rather than a Fitts' law optimization enabler, an approach that was also used to successfully simulate haptic percepts [26].

Haptic Feedback for Pointing Facilitation

Following the ISO standard [30], we use the term *haptic* to refer to two different types of feedback: *tactile* feedback (information received through nerve receptors in the skin) and *kinesthetic* feedback (information sensed through movement and/or force to muscles and joints). Haptic feedback has long been used as an assistive technology for disabled users, or to supplement the visual modality in teleoperation systems and virtual environments. But researchers have also investigated its potential for facilitating routine target acquisition in graphical interfaces.

Discrete $2D$ pointing tasks have received the most attention [3, 2, 24, 28, 16, 22]. But reciprocal $1D$ pointing [13], reciprocal $2D$ pointing and crossing [17], steering [11, 15], as well as ecological tasks [28, 15, 13], have also been studied. The device used for these studies is typically a haptic-enabled mouse. Other devices include a customized trackpoint [11], stylus [17] or trackball [24], a force-feedback joystick [22] and a 6DOF haptic device [28]. Feedback is provided by either exerting a force on the device to constrain its movement [2, 24, 28, 15, 16, 22] or by moving or vibrating a small part of it [3, 2, 11, 13, 17]. In [17], the haptic mechanism was used to confirm the selection of the target. In all the other studies, it was used to provide feedback about the cursor's relative position to the target, or tunnel, during the selection movement.

Haptic feedback has mostly been evaluated against "normal" pointing, i.e. pointing with no additional feedback indicating the cursor is over a target or has been selected. All the above studies showed it can improve users' targeting performance in this context by reducing the overall movement time [2, 11, 15, 16, 22, 13, 17], the time to stop after entering the target [3], or the error rate [28]. Some studies suggest that tactile feedback might be particularly effective at reducing selection times for small targets at the cost of higher error rates, although the reasons for the additional errors remain unclear [2, 13]. It has also been suggested that tactile feedback does not aid in direct input configurations [17].

Moving and vibrating parts of haptic devices usually generate audible sounds that one might want to filter out during experiments [13]. Comparisons of tactile and auditory feedback indeed showed similar positive effects on target acquisition [3, 13]. Tactile feedback has also been compared to visual feedback [3, 11] and CD gain adaptation [13], and researchers have investigated whether these different modalities can combine in a positive way [3, 2, 11, 13]. As Cockburn and Brewster put it, "some do while others do not" and the actual result depends a lot on the nature of the task: a promising technique poorly applied to a simple ecological task can damage interaction by distracting users from it [13].

Most of the devices we mentioned were based on simple and well-tested electromagnetic technologies (e.g. solenoids, voice coils, or vibratory motors with an offset mass). The problem with these technologies is that the haptic sensations they support are rather coarse. Yet recent advances in haptic technologies offer significant promise for extending their use in HCI in general, and pointing facilitation in particular, by supporting more subtle sensations. Recent works on friction reduction are particularly interesting in this context.

While most tactile feedbacks rely on active stimulation using pin-based arrays, Watanabe & Fukui proposed a method to create a smoother feeling on a surface by applying ultrasonic vibration with only a few micrometers amplitude [32]. The perceived feeling, caused by a *squeeze film effect* (Figure 1), has been used recently to simulate bumps and holes [33]. Electrovibration has also been shown to support similar sensations [6]. In contrast to traditional vibrotactile approaches, devices based on these technologies provide information passively, acting as *texture displays* [20]: they do not transfer energy to the user but modify how energy is dissipated within the contact area by a user-initiated friction process.

Impact of Distractors

Target-aware pointing techniques tend to work best on sparse layouts. For intrinsic reasons, many of them do not scale well to situations where multiple potential targets are closely packed together [5]. In real-world applications however, locally dense clusters of potential targets emerge for various reasons [8]. Surprisingly, although the problem is clearly identified in the literature, little research has been done to systematically evaluate the impact of distractors on existing techniques or design new ones that take them into account.

Among the studies of control space techniques and haptic feedback we discussed, a few took distractors explicitly into account – although in limited ways. One variable of the experiments described in [24] and [35] was the presence or absence of a single distractor along the target path (multiple distractors were actually used to make sure one would always be on the path when needed). In [22], one condition involved a distractor located at 180, 90, 0 or -90° relative to the task axis. The second experiment described in [16] displayed 13 targets arranged in a cross shape and required the user to randomly move from one to another, all the others acting as potentially avoidable distractors. The second experiment described in [13] is one of the very few that evaluated the impact of multiple distractors on a control space technique (*sticky targets*) and tactile feedback in a simple ecological task (menu selection). Results from all these studies suggest a negative impact of distractors on movement time, error rate, or user satisfaction. All the authors recommend further investigation.

STIMTAC AND THE SURFPAD TECHNIQUE

Previous research has clearly demonstrated the potential of control space techniques and haptic feedback for pointing facilitation. Yet, the impact of distractors on these techniques remains largely unknown. At the same time, recent advances in haptic technologies offer significant promise for supporting a wider range of sensations and thus more subtle bare-hand interactions. All these elements contributed to our initial motivation for the *Surfpad* technique, which relies on a particular device, the STIMTAC [9].

STIMTAC

The STIMTAC is a touchpad-like device based on the squeeze film effect described above. The tactile plate is made of 36 piezoelectric cells bonded on a $79\ mm \times 49\ mm$ copper–beryllium plate. This monomorph structure constitutes a mechanical resonator excited by a $40\ V$ sinusoidal voltage provided by a $0.5\ W$ power supply (to reduce power consumption, the device can be configured so that it vibrates the plate only if finger contact is detected). The overall design results in a compact and lightweight form factor that

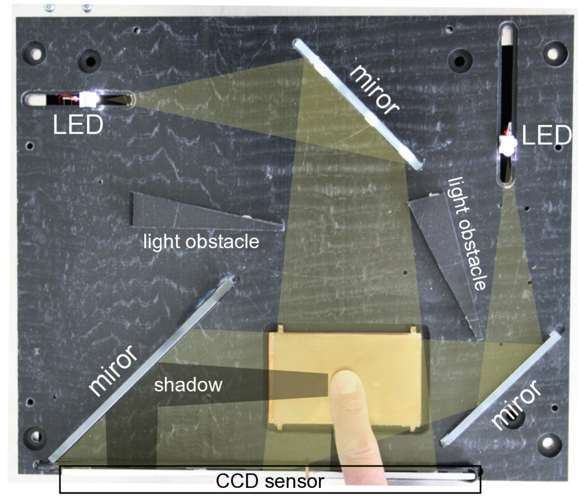

Figure 2. Picture of the STIMTAC device with its shell removed. The shell has only one opening for the tactile surface.

allows free exploration of the tactile surface (Figure 2). The plate is coated with a thin plastic layer to make finger contact more comfortable. It vibrates at the ultrasonic frequency of $28.55\ kHz$ and thus emits no perceptible noise during operation. Since the frequency is outside skin mechanoreceptors' bandwidth, users do not feel the vibration. Instead, they feel its effect on tribological contact mechanisms: the touchpad feels more slippery as one raises the vibration amplitude. The device is typically configured for a maximum amplitude of $1\ \mu m$ which can reduce friction up to 50% depending on surface preparation (e.g. cleaning the surface also affects its coefficient of friction).

Traditional touchpad sensors are incompatible with the squeeze film effect due to the relatively high voltage and frequencies (a resistive sensor would damp the vibrations and a capacitive one would be perturbed by the electric field). A custom-made optical sensor is thus used to locate the user's finger. The sensor was built from two white LEDs, three mirrors and a linear $200\ dpi$ CCD array. An on-board DSP computes the centroids of two shadow images created by the user's finger and sends them on a serial line as absolute (x, y) coordinates at a rate of $120\ Hz$. The final resolution of the sensor is $170\ dpi$ due to optical constraints and post-treatments. The serial line allows to specify the desired coefficient of friction by controling the amplitude at a rate up to $120\ Hz$ using a 7-bit encoded integer between 0 (no squeeze film effect, maximum friction) and 127 (maximum amplitude, maximum effect, minimum friction).

The Surfpad Technique

Tactile feedback through the STIMTAC builds on the relative displacement that exists between a fingertip and a surface when a user is probing for friction. A user moving a finger on the switched-off plate will find it hard, smooth, and not sticky. But, because of its high level of friction, the skin will be stretched laterally, which will become obvious at any direction change. Once the squeeze film effect is activated, the surface retains its original properties but with the reduced friction, the skin becomes less stretched. The sensation can approach the feeling of touching a silk scarf. If the effect is disabled while the finger is moving, the increased amount of friction will be quite noticeable.

Considering these new possibilities, we were excited to investigate ways in which they could be used for pointing facilitation. Influenced by the related work, we started with the idea of designing a target-aware technique. As we saw, many of these techniques operate by modifying the mechanics of motion around targets in the virtual world (for control space techniques) or in the physical one (for haptic techniques). The purpose of the modifications is to facilitate pointing and the desired result is to slow down the cursor or guide its movements. In fact, existing techniques can be thought of as increasing the friction of specific objects.

The STIMTAC can only reduce friction. In order to increase it on specific objects, one needs to decrease it everywhere else. The technique we propose originates from this figure-ground reversal in pointing facilitation: instead of slowing down the cursor around targets, why not facilitate its movement on the background? While most target-aware techniques tend to ignore the background, ours is background-aware. A surfing metaphor seemed appropriate, the low friction background corresponding to the ocean, the objects to the shore, and the finger-controlled cursor to the board.

The *Surfpad* technique uses the programmable squeeze film effect of the STIMTAC to reduce the touchpad's coefficient of friction at all times except when the cursor is over a target. We have implemented it in two ways. Similar to traditional sticky targets, *Surfpad*Π uses the following step function:

$$\textit{Surfpad}\Pi(x) = \begin{cases} 0 & \textit{maximum friction if over a target} \\ 127 & \textit{minimum friction otherwise} \end{cases}$$

Instead of a step function, *Surfpad*Ω uses the Ω bell-shaped mixing function defined in [10] to avoid discontinuities in the amount of friction.

EXPERIMENT 1: SURFPAD

The goal of this first experiment is to investigate the effect of *Surfpad* on performance in a pointing task and compare it to target-aware CD gain adaptation and constant CD gain in the absence of distractors. We used the *Semantic Pointing* technique [10] for target-aware CD gain adaptation as it is well documented and considered as a reference in this domain.

Apparatus

The STIMTAC device described in the previous section was used as the input device for all the techniques to eliminate extraneous intra-devices differences such as ergonomics, size and sensitivity. We used a 15" LCD display at a 1280×800 pixel resolution. The experiment was coded in C++ and OpenGL. The frequency of the visual and haptic renderings were $60\ Hz$ and $120\ Hz$ respectively.

Task

We used a reciprocal one dimensional pointing task (Figure 3). Each trial began after the previous target was successfully selected and ended with the selection of the current target. After a target was successfully selected, it turned grey and the next one (on the other side of the screen) turned green. If a participant missed a target, a sound was heard and an error was logged. Participants had to successfully select the current target before moving to the next one, even if it required multiple clicks. The pointer was not constrained to screen bounds to avoid using the edges to facilitate target acquisition. Participants used the left `Ctrl` key on a keyboard with their non-dominant hand to select targets. After each block of trials, a cumulative error rate was displayed and a message encouraged participants to conform to an approximately 4% error rate by speeding up or slowing down.

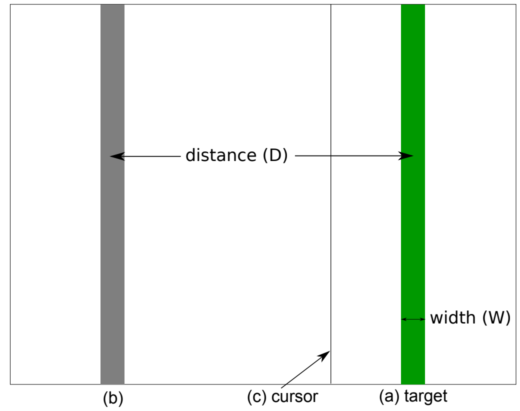

Figure 3. Experimental display. Targets were rendered as solid vertical bars equidistant from the center of the display in opposite directions along the horizontal axis. The target to be selected was colored green (a), and the previous one gray (b). The cursor was represented by a one-pixel-thick vertical black line (c).

Participants

Twelve unpaid volunteers with a mean age of 28.9 ($SD = 7.0$) served in the experiment (9 male and 3 female, 10 right-handed and 2 left-handed).

Design

A repeated measures within-subjects design was used. The independent variables were the technique used (TECHNIQUE) and the target distance (DISTANCE) and width (WIDTH). DISTANCE was evaluated with three levels (D_L = 100 mm, D_M = 50 mm, D_S = 25 mm) and WIDTH as well (W_L = 4.136 mm = 16 pixels, W_M = 2.068 mm = 8 pixels, W_S = 1.034 mm = 4 pixels)[1]. The index of difficulty thus ranged from 2.8 to 6.6.

The techniques were constant CD gain with no actuation of the STIMTAC (*Control*), constant CD gain with full actuation of the STIMTAC (*Control-*), *Semantic Pointing* using the Π step function (*SemPoint*Π), *Semantic Pointing* using the Ω mixing function (*SemPoint*Ω), *Surfpad*Π and *Surfpad*Ω. For *Semantic Pointing*, we chose to quadruple the size of targets in motor space as this was reported by Blanch et al. as yielding the best performance [10]. But while they had set their baseline CD gain to 1, we instead used one of 2 for all techniques to reduce clutching[2] with the largest distance considering the dimensions of our input surface.

[1] All distances and sizes are given in display space.

[2] Clutching consists in temporarily breaking the link between the physical device and the virtual pointer.

Participants had a few minutes to get used to the device in the *Control* condition before starting the experiment. They then completed 4 successive Blocks of trials for each Technique. Each Block consisted of 27 trials: 3 repetitions of the 9 Distance×Width combinations. The Distance and Width were presented in descending order. The presentation order of Technique was counterbalanced across participants using a Latin Square design. Participants were encouraged to take a break every 9 trials. The experiment lasted approximately 50 minutes.

In summary, the experimental design was: 12 participants × 6 Technique × 4 Blocks × 3 Distance × 3 Width × 3 trials = 7,776 total trials.

RESULTS

The dependent variables were the error rate, the movement time, the approaching time, the stopping time, the click time and the clutch time.

Error Rate

Targets that were not selected on the first attempt were marked as errors. Participants emphasized speed over accuracy with an overall error rate of 6.5%. A repeated measures ANOVA showed a significant effect of Width on error rate, the latter increasing as target width decreases ($F_{2,22}$=24.3, $p<0.001$; W_S : 10.9%, W_M : 4.6%, W_L : 3.0%). There was also a significant effect of Technique on error rate ($F_{5,55}$=7.06, $p<0.001$). Post-hoc analysis showed significant differences between *SemPoint*Π and all the other techniques ($p<0.012$; *Control* : 6.4%, *Control-* : 8.6%, *SemPoint*Π : 3.4%, *SemPoint*Ω : 5.0%, *Surfpad*Ω : 7.6%, *Surfpad*Π : 6.0%).

Movement Time

Movement time is the main dependent measure and is defined as the time taken to move from a target to the next one and click on it. Targets marked as errors were removed from the timing analysis. We also considered trials at least three standard deviations away from the mean for each Technique×Distance×Width condition as outliers and removed them from the data analysis (1.6% of the trials).

A repeated measures ANOVA showed that the presentation order of Technique had no significant effect or interaction on movement time, indicating that a within-participants design was appropriate. We also found no significant effect or interaction for Block indicating there was no presence of a learning effect.

A repeated measures ANOVA showed a significant effect of Technique on movement time ($F_{5,55}$=14.2, $p<0.001$). Pairwise comparisons showed no significant difference between *Surfpad*Ω and *Surfpad*Π (p=0.09), but while *Surfpad*Π was significantly different from all the other techniques ($p<0.03$), *Surfpad*Ω was only significantly different from *SemPoint*Π and *SemPoint*Ω ($p<0.009$). No significant difference was found between *SemPoint*Π and *SemPoint*Ω, but significant differences were found between these variants and the others techniques ($p<0.008$). No significant difference was found between *Control* and *Control-*, but significant differences were found between these two techniques and the others ($p<0.012$)

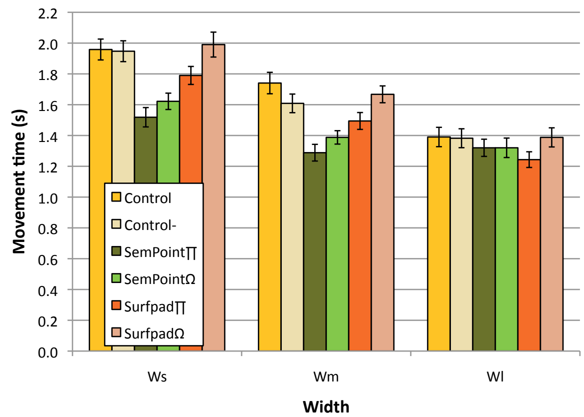

Figure 4. Mean movement time for Technique and Width. Error bars represent 95% confidence interval.

except *Surfpad*Ω (*Control* : 1.58s, *Control-* : 1.58s, *SemPoint*Π : 1.29s, *SemPoint*Ω : 1.31s, *Surfpad*Ω : 1.57s, *Surfpad*Π : 1.44s).

As predicted by Fitts' law, there was significant main effects of Distance ($F_{2,22}$=106.4, $p<0.001$) and Width ($F_{2,22}$=57.6, $p<0.001$) and a significant Distance×Width interaction ($F_{4,44}$=7.4, $p<0.001$). More interestingly, we also observed a Technique×Width interaction ($F_{10,110}$=11.2, $p<0.001$, Figure 4). Subsequent pairwise comparisons showed significant differences between the techniques as Width gets smaller. For W_L, there was no significant difference between techniques except between *Surfpad*Π and *Surfpad*Ω (1.34s vs. 1.17s, p=0.032). For W_M and W_S, we observed similar patterns. There was no significant difference between the two control conditions and no significant difference between *SemPoint*Π and *SemPoint*Ω. We found a significant difference between *Surfpad*Π (1.39s) and *Surfpad*Ω (1.55s) for W_M (p=0.03), but not for W_S. For W_M and W_S, *Surfpad*Π, *SemPoint*Π and *SemPoint*Ω significantly improved movement time compared to the two control conditions ($p<0.05$). On these target sizes, *SemPoint*Π and *SemPoint*Ω were significantly better than *Surfpad*Π ($p<0.02$).

To better understand the effects observed on movement time, we split it in three parts: *approaching time*, *stopping time* and *click time*. As we noticed participants clutching during the experiment, we also analyzed the corresponding time.

Approaching Time

Approaching time is the time between the beginning of the movement and the instant the target border is crossed. There was a significant main effect of Technique ($F_{5,55}$=7.9, $p<0.001$), Distance ($F_{2,22}$=229.2, $p<0.001$) and Width ($F_{2,22}$=17.5, $p<0.001$) on it as well as significant Technique×Width ($F_{10,110}$=18.6, $p<0.001$) and Distance×Width ($F_{4,44}$=11.4, $p<0.001$) interactions. Pairwise comparisons showed significant differences between the techniques in a trend similar to the one observed for movement time. In particular, *SemPoint*Π, *SemPoint*Ω and *Surfpad*Π showed a significantly lower approaching time compared to the two control conditions ($p < 0.05$). Pairwise comparisons showed that approaching time increased with larger target distances and smaller target widths.

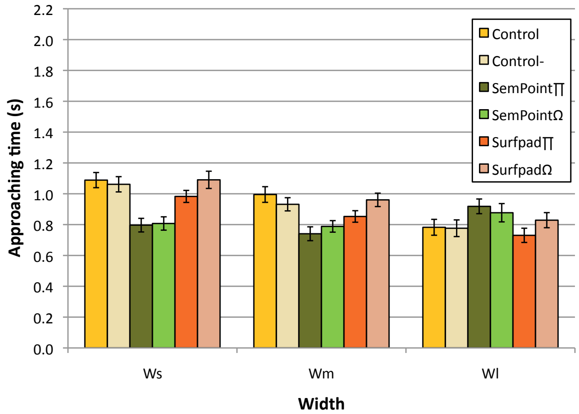

Figure 5. Mean approaching time for TECHNIQUE and WIDTH. Error bars represent 95% confidence interval.

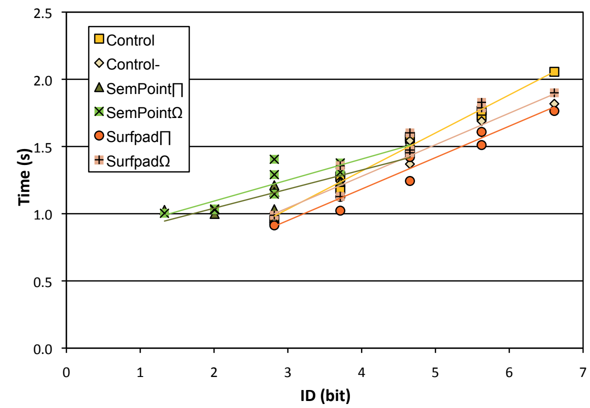

Figure 6. Fitts'law regression for each TECHNIQUE. IDs were computed in visual space for *Control*, *Control-*, *Surfpad*Ω and *Surfpad*Π and motor space for *SemPoint*Π and *SemPoint*Ω.

More surprisingly the TECHNIQUE×WIDTH interaction exhibited a different behavior for *SemPoint*Π and *SemPoint*Ω for W_L with a significantly higher approaching time compared to *Control*, *Control-* and *Surfpad*Π ($p<0.008$, Figure 5). This result might explain why no significant difference was found for the movement time on W_L between the *Semantic Pointing* variants and the two control conditions.

Stopping Time

Stopping time is the time between the first crossing of the target border and the stopping of the cursor. We observed a significant main effect of TECHNIQUE on it ($F_{5,55}$=3.7, p=0.038; *Control* : 0.44s, *Control-* : 0.44s, *SemPoint*Π : 0.34s, *SemPoint*Ω : 0.34s, *Surfpad*Ω : 0.41s, *Surfpad*Π : 0.36s). Pairwise comparisons showed significant differences ($p<0.05$) between the *Semantic Pointing* variants and the control conditions as well as *Surfpad*Ω. We also observed significant differences between *Surfpad*Π and the two control conditions ($p<0.02$). These results might partially explain the significant differences observed for the movement time.

We also found a significant main effect of WIDTH ($F_{5,55}$=20.1, p=0.001) on stopping time, the latter increasing with smaller widths. Pairwise comparisons showed significant differences between W_S and the two other widths (W_S = 0.48s, W_M = 0.36s, W_L = 0.33s; $p<0.004$).

Click Time

Click time is the time during which the pointer remains still before the button is pressed. We observed significant effects of TECHNIQUE ($F_{5,55}$=9.9, $p<0.001$) and WIDTH ($F_{2,22}$=210.4, p=0.001) on it. Pairwise comparisons showed significant differences between the *Semantic Pointing* variants and the other techniques (*SemPoint*Π = 0.15s, *SemPoint*Ω = 0.16s, *Control* = 0.20s, *Control-* = 0.19s, *Surfpad*Π = 0.21s, *Surfpad*Ω = 0.19s; $p<0.02$). This result might explain the significant difference observed between the *Semantic Pointing* variants and *Surfpad*Π for the movement time. There were significant differences between the widths, the click time increasing as the target width decreases (W_S = 0.24s, W_M = 0.18s, W_L = 0.13s; $p<0.001$).

Clutch Time and Number of Clutches

Clutch time is the total time the finger is lifted during a trial. There was a significant effect of DISTANCE ($F_{2,22}$=10.2, p=0.003) on it. Pairwise comparisons showed that it increases with larger target distances, with significant differences between all distances (D_S=0.018, D_M=0.045, D_L=0.147; $p<0.034$). There was also a significant effect of DISTANCE ($F_{2,22}$=6.2, p=0.014) on the number of clutches. Pairwise comparisons showed significant differences between all distances (D_S=0.36, D_M=0.58, D_L=1.73; $p<0.05$). Although not significant, we observed that the clutch time increased with target width (W_S=0.057s, W_M=0.062s, W_L=0.079s).

Fitts' Law Analysis

We ran a Fitts' law analysis on movement time removing trials where an error or clutching occured. For *SemPoint*Π and *SemPoint*Ω, we computed the index of difficulty in motor space, as suggested in [10]. We aggregated the data for each target width and distance, producing a total of 9 points for each TECHNIQUE. As shown on Figure 6, we obtained good regression fitness for *Control* ($MT = 0.185 + 0.283\,ID$, $r^2 = 0.98$), *Control-* ($MT = 0.339 + 0.235\,ID$, $r^2 = 0.90$), *Surfpad*Ω ($MT = 0.295 + 0.258\,ID$, $r^2 = 0.92$) and *Surfpad*Π ($MT = 0.247 + 0.234\,ID$, $r^2 = 0.93$), but reduced regression fitness for *SemPoint*Π ($MT = 0.756 + 0.142\,ID$, $r^2 = 0.84$) and *SemPoint*Ω ($MT = 0.781 + 0.156\,ID$, $r^2 = 0.79$). These last two results are mainly explained by the outlier point (D_L,W_L) for which we have the highest amount of clutching.

DISCUSSION

The experiment compared six techniques with the same baseline CD gain. No significant difference was found between the two control conditions. Our results show that *Surfpad*Π and the two *Semantic Pointing* variants significantly improve performance by 8.8% and 17.7% respectively, compared to the control conditions. *Surfpad*Ω did not result in any significant performance improvement compared to the control conditions. Results also show that these differences can be explained by a significant decrease in approaching time and stopping time for *Surfpad*Π, *SemPoint*Π and *SemPoint*Ω compared to the control conditions, and a significant decrease in click time for *SemPoint*Π and *SemPoint*Ω compared to the other techniques.

Mechanical Effect or Information Feedback?

Our results do not show any significant difference between *Control* and *Control-* for movement time, approaching time, stopping time or click time. This inclines us to conclude that the friction reduction provided by the full actuation of the STIMTAC does not help to achieve faster movements.

The approaching time is significantly lower for *SemPoint*Π and *SemPoint*Ω than for the control conditions. As the step function and the bell-shaped mixing function operate only in the close vicinity of the targets, we assume this is the consequence of an anticipation phenomenon already observed in the use of *expanding targets* [27].

The approaching time is also significantly lower for *Surfpad*Π than for the control conditions. As friction reduction does not help to achieve faster movements, we assume this is also caused by anticipation of some later perceivable effect. Since the approaching time for *Surfpad*Ω is not significantly different from the control conditions, the perceived effect must be inherent to the Π function and incompatible with the Ω one.

Our results show a significantly lower stopping time for *Surfpad*Π compared to the control conditions. We hypothesize two reasons for this: (H1) a mechanical braking effect related to the friction increase, or (H2) tactile information feedback, i.e. a cognitive response to the perception of this increase. Although Π and Ω differ, their integral is the same[3]. From a mechanical perspective, the braking effect of H1 should also be observed with *Surfpad*Ω, which was not the case. H1 is also contradicted by the fact that *Surfpad*Π is more efficient on small target sizes where it should be more difficult to take advantage of a mechanical effect. We thus favor the second hypothesis, H2, which is also supported by previous evidence that the addition of tactile information can reduce response times by providing a confirmation without the need for visual attention [3, 17].

Target Size Matters

We observed a significant interaction between target sizes and techniques on movement time. Compared to the two control conditions, the mean movement time for target sizes W_M and W_S is reduced by 8.8% for *Surfpad*Π and 17.7% for the *Semantic Pointing* variants. Yet the three techniques fall short for W_L although according to Blanch et al., *Semantic Pointing* reduces the index of difficulty in motor space independently of target width [10].

Although clutching remained limited, we hypothesize that the slightly higher amount of it observed for W_L may have disrupted finger movements. Further experiments are required to validate this hypothesis. Still, the more pronounced effect of *Surfpad*Π as target width decreases agrees with results from previous work on tactile feedback [2].

EXPERIMENT 2: ANTI-SURFPAD

Results from Experiment 1 suggest that the performance improvement observed with *Surfpad*Π is the result of information feedback provided by the sudden increase of friction when the cursor crosses the target border. This second experiment was designed to better understand the nature of this feedback. We wanted to investigate if it can also be provided by a sudden decrease of friction. We call this condition *Anti-Surfpad*Π: the friction is minimal if the cursor is over a target, and maximal otherwise.

The apparatus and task for this experiment were the same as in the first one. The techniques were *Control*, *Surfpad*Π and *Anti-Surfpad*Π. Nine participants with a mean age of 27.3 (SD=4.7) took part in the experiment (8 male and 1 female, 8 right-handed and 1 left-handed).

A repeated measures ANOVA showed a significant main effect of TECHNIQUE ($F_{2,16}$=17.8, $p<0.001$) and a significant TECHNIQUE×WIDTH interaction ($F_{4,32}$=4.4, $p=0.02$) on the movement time. Significant differences were found between the three techniques (*Control*=1.60s, *Anti-Surfpad*Π=1.82s, *Surfpad*Π=1.49s; $p<0.007$). The significant interaction showed that *Anti-Surfpad*Π increased the movement time for all target widths ($p<0.05$). *Surfpad*Π significantly improved performance compared to *Control* and *Anti-Surfpad*Π for W_S and W_M ($p<0.009$). However, the difference with *Control* was no longer significant for W_L.

A repeated measures ANOVA also showed a significant main effect of TECHNIQUE ($F_{2,16}$=17.8, $p<0.001$) on stopping time with significant differences between all techniques (*Control*=0.46s, *Surfpad*Π=0.39s, *Anti-Surfpad*Π=0.60s, $p<0.01$). We again hypothesize two reasons for this: (H3) a negative mechanical effect stronger than the information feedback, or (H4) counter-effective information feedback. Further experimentation is needed to validate these compatible hypotheses.

EXPERIMENT 3: DISTRACTORS

In Experiment 1, we showed that *Surfpad*Π and the *Semantic Pointing* variants significantly improve the movement time compared to the two control conditions, especially for small target sizes. The goal of this third experiment was to investigate the impact of distractors on the *Surfpad* and *Semantic Pointing* techniques.

As we found no significant difference between *SemPoint*Ω and *SemPoint*Π in Experiment 1, we decided to focus on *SemPoint*Ω which is the implementation described in [10]. We also decided to focus on *Surfpad*Π since it showed significant differences with the control conditions in Experiment 1 while *Surfpad*Ω did not show any. *Surfpad* and *Semantic Pointing* will thus refer to *Surfpad*Π and *SemPoint*Ω in this section. Lastly, as we found no significant difference between *Control* and *Control-*, we decided to focus on *Control* which corresponds to the default state of the STIMTAC.

Apparatus and Task

We used the exact same apparatus as in Experiment 1 and 2. The task was also the same except for the presence of distractors evenly spaced between the two opposite clickable targets (Figure 7).

Participants

Twelve unpaid volunteers with a mean age of 28 ($SD = 9$) served in the experiment (10 male and 2 female, 9 right-handed and 3 left-handed).

[3]Friction depends on control input nonlinearly for variable friction devices. In the case of the STIMTAC however, the non-linearity is negligible. The difference between the integrals of *Surfpad*Π and *Surfpad*Ω is below 1%.

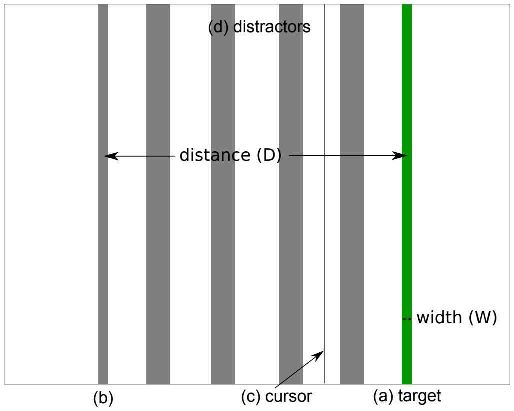

Figure 7. Experimental display. Targets were rendered as solid vertical bars equidistant from the center of the display in opposite directions along the horizontal axis. The target to be selected was colored green (a) and the last target gray (b). The cursor was represented by a one-pixel-thick vertical black line (c). Distractors (d) were evenly spaced between the targets (a) and (b) and were also colored gray.

Design

A repeated measures within-subjects design was used. The independent variables were TECHNIQUE, target width (WIDTH) and distractor density (DENSITY). TECHNIQUE was evaluated with three levels (*Control*, *Semantic Pointing*, *Surfpad*), WIDTH with two levels (W_L = 4.136 mm = 16 pixels, W_S = 1.034 mm = 4 pixels) and DENSITY with 6 levels (0, 1, 2, 4, 8, 12). The distractors were evenly spaced between the extremum targets with a size equal to W_L across all conditions. We used this width and these densities for distractors as they are representative of buttons size and densities in toolbars or menus. The target distance was kept constant to 100 mm to allow evaluating the different distractor densities while keeping a reasonably small amount of clutching.

Participants had a few minutes to get used to the device in the *Control* condition before starting the experiment. They then completed four successive BLOCKS of trials for each TECHNIQUE. Each BLOCK consisted of 36 trials: 3 repetitions of the 6 DENSITY $\times$ 2 WIDTH combinations. The WIDTH was presented in descending order and the DENSITY in ascending order. The presentation order of TECHNIQUE was counterbalanced across participants using a Latin Square design. Participants were encouraged to take a break after every 6 trials. The experiment lasted approximately 35 minutes.

In summary, the experimental design was: 12 participants $\times$ 3 TECHNIQUE $\times$ 4 BLOCKS $\times$ 2 WIDTH $\times$ 6 DENSITY $\times$ 3 trials $= 5,184$ total trials

RESULTS

The dependent variables were the error rate, the movement time, the clutch time and the overshooting distance. They were computed the same way as in Experiment 1.

Error Rate

A repeated measures ANOVA showed a significant effect of WIDTH ($F_{1,11}$=96.3, $p<0.001$) on error rate with significant difference between W_S (10.2%) and W_L (1.9%) and an overall error rate of 6.1%.

Movement Time

Targets marked as errors were removed from the timing analysis. Trials at least three standard deviations away from the mean for each condition were considered as outliers and also removed from the data analysis (1.5% of the trials).

A repeated measures ANOVA showed that the order of presentation of TECHNIQUE had no significant effect or interaction on movement time, indicating that a within-participants design was appropriate. We also found no significant effect or interaction for BLOCK indicating there was no presence of a learning effect. As predicted by Fitts' law, a repeated measures ANOVA found a significant effect of WIDTH ($F_{1,11}$=199.4, $p<0.001$) on movement time with the smaller width increasing the movement time.

There was a significant main effect for TECHNIQUE ($F_{2,22}$ =119.1, $p<0.001$) and DENSITY ($F_{5,55}$=67.8, $p<0.001$) and a significant TECHNIQUE$\times$DENSITY interaction ($F_{10,110}$=92.6, $p<0.001$) on movement time (Figure 8). Pairwise comparison showed significant differences ($p<0.001$) between all techniques: 2.1s for *Control*, 2.9s for *Semantic Pointing*, and 1.9s for *Surfpad*. It shows that *Surfpad* improves performance by 9.5% compared to *Control* and 52.6% compared to *Semantic Pointing*. *Semantic Pointing* deteriorates performance by 38.1% compared to *Control*.

Subsequent pairwise comparison for the significant TECHNIQUE $\times$ DENSITY interaction showed that the degradation of performance for *Semantic Pointing* increased with DENSITY. No significant difference between techniques was found for density 0, but we found significant differences ($p<0.04$) between *Control* and *Surfpad* for densities greater than 1. Significant differences ($p<0.03$) were found between DENSITY levels for *Semantic Pointing* except between 0 and 1 (p=0.16), and 2 and 4 (p=0.07). No significant difference was found between DENSITY levels for *Control* and *Surfpad*.

Clutch Time

A repeated measures ANOVA showed a significant main effect of TECHNIQUE ($F_{2,22}$=64.4, $p<0.001$) and DENSITY ($F_{5,55}$=164.4, $p<0.001$) and a significant TECHNIQUE$\times$DENSITY interaction ($F_{10,110}$=121.9, $p<0.001$) on clutch time. Pairwise comparison showed significant differences ($p<0.001$) between

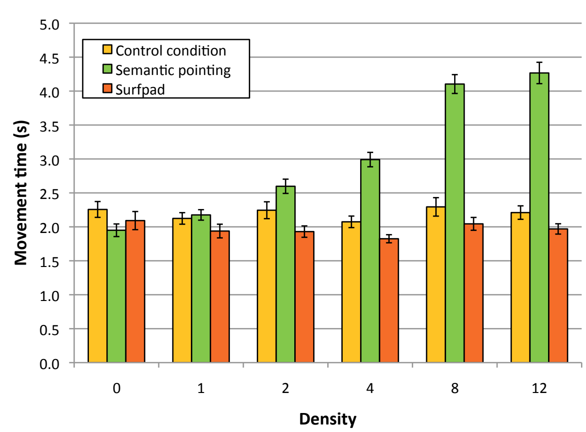

Figure 8. Mean movement time for TECHNIQUE and DENSITY. Error bars represent 95% confidence interval.

Semantic Pointing (0.59s), *Surfpad* (0.12s) and *Control* (0.15s). No significant difference was found across DENSITY for *Surfpad* or *Control*, but we found significant differences ($p<0.003$) between the following density groups for *Semantic Pointing*: (0,1): 0.28s, (2): 0.42s, (4): 0.54s, (8,12): 1.02s (Figure 9).

Overshooting Distance

We define overshooting as the distance traveled past the extend of the target. A repeated measures ANOVA showed no significant main effect or interaction on the overshooting distance. The mean overshooting distance was equal to 1.7 mm (SD=4.8 mm) and the 90^{th} percentile was equal to 4.8 mm. The 90^{th} percentile for overshooting was equal to 3.7 mm in Experiment 1 and 3.4 mm in Experiment 2. Considering this relatively small overshooting distance, users' strategy to acquire the target was probably not to overshoot the target and then correct to select it.

User Feedback

Most of participants comments on *Semantic Pointing* concerned the clutching required to move the pointer, especially when the number of distractors becomes important. Participants did not spontaneously comment on distractors for *Surfpad*. After debriefing, they explained they did not feel disrupted in their movement by the tactile feedback on distractors. Participants were also asked which technique they would use. Eleven chose *Surfpad* and one chose *Control*.

DISCUSSION

We compared *Surfpad* to *Control* and *Semantic Pointing* in the same conditions as in the first experiment with additional control on the density of distractors. Our results show that *Surfpad* significantly improves the movement time by 9.5% compared to *Control*, independently of the density of distractors. In contrast, we showed that *Semantic Pointing* significantly degrades the movement time compared to *Control* with a rate related to the density of distractors (from 22.4% for density 2 to 100% for density 12). Results show that the significant increase in clutching for *Semantic Pointing* compared to *Surfpad* and *Control* can be held responsible to its significant increase of movement time.

In the worse case scenario for *Semantic Pointing*, the distance to the target gets fully covered with distractors: the indices of difficulty in motor and display spaces become equal (considering there is no overlapping between distractors), but the distance in motor space gets multiplied by the scale factor. Such a situation typically occurs in hierarchical menus [13]. If the device operating range is set to cover the entire display surface without clutching, multiplying the distance by the scale factor in motor space will inevitably lead to clutching and a deterioration of performance.

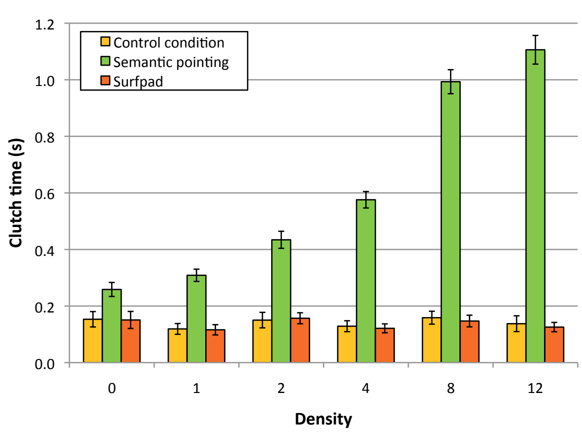

Figure 9. Mean clutch time for TECHNIQUE and DENSITY. Error bars represent 95% confidence interval.

There was no negative effect of distractors on *Surfpad* which still showed a significant improvement of 9.5% on movement time compared to *Control* in their presence. This reinforces our belief that the *Surfpad*Π implementation mainly provides information feedback and little or no mechanical effect. Participants did not make any negative comment on the tactile feedback associated to distractors. This makes *Surfpad* a good alternative to *Semantic Pointing* and probably target-aware CD gain adaptation in general, especially for limited workspaces where clutching is likely to occur in presence of distractors.

CONCLUSION AND DIRECTIONS FOR FUTURE WORK

We presented *Surfpad*, a new pointing facilitation technique based on STIMTAC, a tactile touchpad that supports friction reduction. *Surfpad* preserves the nominal coefficient of friction of the touchpad when the cursor is on targets but reduces it in all other places. We reported on three experiments comparing it to *Semantic Pointing* and constant CD gain. Our results show that *Surfpad* leads to a performance improvement close to 9% compared to unassisted pointing on small targets without distractors. It is also robust to high distractor densities, keeping an average performance improvement of nearly 10% whereas the performance of *Semantic Pointing* can degrade up to 100% due to increased clutching caused by distractor expansion in motor space. Our results also show that *Surfpad* needs to be implemented using a step function (*Surfpad*Π) to improve performance.This implementation provides a sudden reduction in the amount of friction when the pointer crosses the target border which, we hypothesize, results in an information feedback that helps users reduce the approaching and stopping times.

Surfpad's robustness to distractors is particularly novel. This characteristic has exciting implications since it no longer requires the careful determination of targets to enable a pointing facilitation technique. Our prototype STIMTAC device can be easily carried for demonstrations, but it is still too large to incorporate in a mobile computing device such as a laptop. New prototypes are being developed which use more compact sensing techniques. Once the size is reduced, its low power consumption ($0.5\ W$) makes it feasible to use in place of a conventional laptop touchpad. However, the tactile feedback it provides is intrinsically mono-touch. The extension to multi-touch will be addressed as future work.

Acknowledgments

This work was supported by the ANR project n°ANR-09-CORD-013 "InSTInCT".

REFERENCES

1. D. Ahlström, M. Hitz, and G. Leitner. An evaluation of sticky and force enhanced targets in multi target situations. In *Proc. of NordiCHI'06*, 58–67. ACM.

2. M. Akamatsu and I. S. MacKenzie. Movement characteristics using a mouse with tactile and force feedback. *IJHCS*, 45(4):483–493, 1996.
3. M. Akamatsu, I. S. MacKenzie, and T. Hasbrouc. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics*, 38(4):816–827, 1995.
4. T. Asano, E. Sharlin, Y. Kitamura, K. Takashima, and F. Kishino. Predictive interaction using the delphian desktop. In *Proc. of UIST'05*, 133–141. ACM, 2005.
5. R. Balakrishnan. "Beating" Fitts' law: virtual enhancements for pointing facilitation. *IJHCS*, 61(6):857–874, 2004.
6. O. Bau, I. Poupyrev, A. Israr, and C. Harrison. Teslatouch: electrovibration for touch surfaces. In *Proc. of UIST'10*, 283–292. ACM, 2010.
7. P. Baudisch, E. Cutrell, M. Czerwinski, D. C. Robbins, P. Tandler, B. B. Bederson, and A. Zierlinger. Drag-and-pop and drag-and-pick: techniques for accessing remote screen content on touch- and pen-operated systems. In *Proc. of Interact'03*, 57–64. IOS Press, 2003.
8. P. Baudisch, A. Zotov, E. Cutrell, and K. Hinckley. Starburst: a target expansion algorithm for non-uniform target distributions. In *Proc. of AVI'08*, 129–137. ACM.
9. M. Biet, F. Giraud, and B. Semail. Squeeze film effect for the design of an ultrasonic tactile plate. *IEEE Transactions on Ultrasonic, Ferroelectric and Frequency Control*, 54(12):2678–2688, 2007.
10. R. Blanch, Y. Guiard, and M. Beaudouin-Lafon. Semantic pointing: improving target acquisition with control-display ratio adaptation. In *Proc. of CHI'04*, 519–526. ACM, 2004.
11. C. S. Campbell, S. Zhai, K. W. May, and P. P. Maglio. What you feel must be what you see: Adding tactile feedback to the trackpoint. In *Proc. of Interact'99*, 383–390. IOS Press, 1999.
12. G. Casiez, D. Vogel, R. Balakrishnan, and A. Cockburn. The impact of control-display gain on user performance in pointing tasks. *Human-Computer Interaction, Taylor and Francis*, 23(3):215–250, 2008.
13. A. Cockburn and S. Brewster. Multimodal feedback for the acquisition of small targets. *Ergonomics*, 48(9):1129–1150, 2005.
14. A. Cockburn and A. Firth. Improving the acquisition of small targets. In *Proc. of HCI'03*, 77–80. BCS, 2003.
15. J. T. Dennerlein, D. B. Martin, and C. Hasser. Force-feedback improves performance for steering and combined steering-targeting tasks. In *Proc. of CHI'00*, 423–429. ACM, 2000.
16. J. T. Dennerlein and M. C. Yang. Haptic force-feedback devices for the office computer: Performance and musculoskeletal loading issues. *Human Factors*, 43(2):278–286, 2001.
17. C. Forlines and R. Balakrishnan. Evaluating tactile feedback and direct vs. indirect stylus input in pointing and crossing selection tasks. In *Proc. of CHI'08*, 1563–1572. ACM, 2008.
18. T. Grossman and R. Balakrishnan. The bubble cursor: enhancing target acquisition by dynamic resizing of the cursor's activation area. In *Proc. of CHI'05*, 281–290. ACM, 2005.
19. Y. Guiard, R. Blanch, and M. Beaudouin-Lafon. Object pointing: a complement to bitmap pointing in GUIs. In *Proc. of GI'04*, 9–16. CHCCS, 2004.
20. C. Harrison and S. E. Hudson. Texture displays: a passive approach to tactile presentation. In *Proc. of CHI'09*, 2261–2264. ACM, 2009.
21. A. Hurst, J. Mankoff, A. K. Dey, and S. E. Hudson. Dirty desktops: using a patina of magnetic mouse dust to make common interactor targets easier to select. In *Proc. of UIST '07*, 183–186. ACM, 2007.
22. F. Hwang, S. Keates, P. M. Langdon, and P. J. Clarkson. Multiple haptic targets for motion-impaired computer users. In *Proc. of CHI'03*, 41–48. ACM, 2003.
23. P. Kabbash and W. Buxton. The "prince" technique: Fitts' law and selection using area cursors. In *Proc. of CHI'95*, 273–279. ACM/Addison-Wesley, 1995.
24. D. V. Keyson. Dynamic cursor gain and tactual feedback in the capture of cursor movements. *Ergonomics*, 40(12):1287 – 1298, 1997.
25. M. Kobayashi and T. Igarashi. Ninja cursors: using multiple cursors to assist target acquisition on large screens. In *Proc. of CHI'08*, 949–958. ACM, 2008.
26. A. Lécuyer, J.-M. Burkhardt, and L. Etienne. Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures. In *Proc. of CHI'04*, 239–246. ACM, 2004.
27. M. J. McGuffin and R. Balakrishnan. Fitts' law and expanding targets: experimental studies and designs for user interfaces. *ACM ToCHI*, 12(4):388–422, 2005.
28. I. Oakley, M. R. McGee, S. Brewster, and P. Gray. Putting the feel in 'look and feel'. In *Proc. of CHI'00*, 415–422. ACM, 2000.
29. R. W. Soukoreff and I. S. MacKenzie. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *IJHCS*, 61(6):751–789, 2004.
30. J. B. F. van Erp, K.-U. Kyung, S. Kassner, J. Carter, S. A. Brewster, G. Weber, and I. Andrew. Setting the standards for haptic and tactile interactions: ISO's work. In *Proc. of EuroHaptics'10*, 353–358. Springer.
31. K. van Mensvoort. What you see is what you feel: exploiting the dominance of the visual over the haptic domain to simulate force-feedback with cursor displacements. In *Proc. of DIS'02*, 345–348. ACM.
32. T. Watanabe and S. Fukui. A method for controlling tactile sensation of surface roughness using ultrasonic vibration. In *Proc. of ICRA'95*, 1134–1139. IEEE.
33. L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin. T-pad: Tactile pattern display through variable friction reduction. In *Proc. of World Haptics Conf.*, 421–426. IEEE, 2007.
34. J. O. Wobbrock, J. Fogarty, S.-Y. Liu, S. Kimuro, and S. Harada. The angle mouse: target-agnostic dynamic gain adjustment based on angular deviation. In *Proc. of CHI'09*, 1401–1410. ACM, 2009.
35. A. Worden, N. Walker, K. Bharat, and S. Hudson. Making computers easier for older adults to use: area cursors and sticky icons. In *Proc. of CHI'97*, 266–271. ACM, 1997.