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Domaine : Perception, cognition, interaction
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Abstract: Ultra-high-resolution wall displays have proven useful for displaying large quantities of information, but lack appropriate interaction techniques to manipulate the data efficiently. We explore the limits of existing modeless remote pointing techniques, originally designed for lower resolution displays, and show that they do not support high-precision pointing on such walls. We then consider techniques that combine a coarse positioning mode to approach the target's area with a precise pointing mode for acquiring the target. We compare both new and existing techniques through a controlled experiment, and find that techniques combining ray casting with relative positioning or angular movements enable the selection of targets as small as 4 millimeters while standing 2 meters away from the display.

Key-words: pointing, large display, ultra-high resolution, dual-mode

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Precision Pointing for Ultra-High-Resolution Wall Displays

Résumé : Les murs d'images à très haute résolution permettent d'afficher de grands jeux de données, mais les techniques d'interaction permettant de manipuler ces données sont encore insuffisantes. Nous explorons les limites des techniques de pointage à distance existantes, originellement destinées à des surfaces d'affichage de résolution plus faibles, et montrons qu'elles ne passent pas à l'échelle. Nous étudions ensuite des techniques qui combinent un mode rapide, pour approcher rapidement de la cible, et un mode précis pour acquérir la cible. Nous comparons cette approche et les techniques existantes dans une expérience contrôlée : la combinaison de "ray-casting" (lancer de rayon) et d'une technique relative basée sur la position ou la rotation permet à un utilisateur se tenant à deux mètres de la surface d'affichage de sélectionner des cibles de 4 millimètres.

Mots-clés : pointing, large display, ultra-high resolution, dual-mode

1 Introduction

Ultra high-resolution display walls [24] are becoming popular to visualize massive datasets. Such displays are usually made of tiled LCD panels with over 100 million pixels (Fig. 1). Thanks to their extremely high resolution, typically 100 dots per inch, they can display large datasets with a high level of detail while retaining context, and enable the juxtaposition of data presented in various forms [1], including small textual elements that remain perfectly legible.

These displays are well-suited to the visualization of, e.g., very large maps and networks (Fig. 1), complex molecule simulations, or astronomy imagery with associated metadata from astronomical catalogs. The combination of large size and high resolution affords a natural form of multiscale interaction: simply by walking, a user can smoothly transition from an overview of the whole display when standing at a distance to the fine details of a specific area by getting up close [3, 36]. It is thus crucial that users be able to point at very small objects on the screen efficiently while standing, whether they are far away or within arm's reach [33]. Finally, the large size makes these displays well-suited to collaborative work; several users must thus be able to point simultaneously, and the pointing techniques must not hinder other tasks to be carried out.

Distant pointing at large displays has been studied in various contexts, ranging from low resolution displays to high-resolution back-projected walls. It has not been studied, however, in the context of ultra-high resolution walls that can display much smaller visual elements that users must still be able to select.

The well-known ray-casting technique, also called laser pointing [23, 27, 28], extends the user's arm or a hand-held device with an imaginary ray whose intersection with the wall display is highlighted. Ray casting degrades quickly with distance to the wall, because hand tremor and involuntary motion due to fatigue are amplified as the user is farther away from the display surface [23, 27]. It is therefore not adapted to

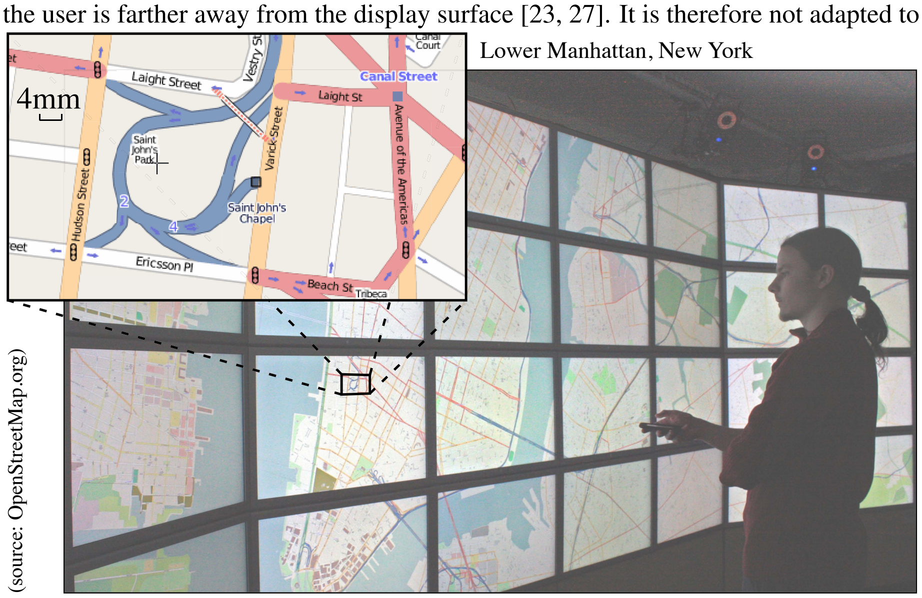

Figure 1: The interactive wall-sized (5.5m × 1.8m) ultra-high-resolution (20 480 × 6 400 = 131 million pixels) display used for our studies. Inset: magnification of a 9cm × 5cm area.

ultra-high-resolution displays. Relative techniques [16, 20] achieve better precision but do not scale to large surfaces because of the need for clutching [12]. Some techniques combine absolute and relative pointing [22, 33], but have been designed and evaluated on displays that were either significantly smaller, or of lower resolution, or both. It is unclear how they fare in the context of ultra-high-resolution, very large displays.

This paper addresses the problem of high-precision pointing on large, ultra-high resolution wall displays: given the very high pixel density, can we design pointing techniques that enable efficient selection of both large and small targets at a distance? We investigate this question by first identifying the limits of modeless techniques in a formative user study. We then consider techniques that feature two levels of precision, a coarse positioning mode to approach the area of the target and a precise pointing mode for acquiring the target, with a method to calibrate the parameters of those two modes. We introduce new techniques and compare them to adaptations of existing ones [17, 33]. We find that techniques combining ray casting for coarse pointing and relative position or angular movements for precise adjustments of the cursor's position, enable the selection of targets as small as 4 millimeters while standing 2 meters away from the display. In comparison, the smallest target sizes reported in earlier studies on wall displays range from 9 centimeters [14] to 1.6 centimeters [33]. Finally, we propose a model for predicting pointing time for these dual-precision techniques.

2 RELATED WORK

We describe physical input devices that have been explored over the past ten years and briefly cover pointing facilitation techniques.

Direct techniques that use a pen [18] or fingers [9, 32] require users to stand within physical reach of the display. With HybridPointing [16], users can reach distant objects by switching from absolute to relative pointing, but the technique still requires direct contact of the pen with the display surface.

Early work on absolute pointing from a distance focused on laser pointers [19]. Olsen *et al.* [28] adapted existing interaction techniques to the limitations of this technology. Both Chen *et al.* [13] and Oh *et al.* [27] designed collaborative pointing devices based on laser pointers, enabling several users to interact with the display simultaneously. The latter also compared a laser pointer to a conventional mouse in a pointing task. The laser performed significantly worse than the mouse on a 1.83m $\times$ 1.22m low-resolution back-projected screen, but was preferred by users. This evaluation built on earlier work by MacKenzie and Jusoh [20], who compared a regular mouse to a gyro-mouse (using gyroscopic sensors) held on a table and then in mid-air, and to a handheld isometric joystick. The task was performed 1.52m away from a 15" screen. The joystick and the gyro-mouse held in mid-air performed poorly compared to the mice. Myers *et al.* [23] studied the effect of human body limitations on laser pointing. They compared the pointing performance of a laser pointer, a regular mouse, a touch-sensitive SmartBoard™ and *Semantic snarfing*. With the latter, users point with a stylus on a handheld that displays a copy of a region from the main screen. The technique requires users to look at the handheld device, causing problems of divided attention. Direct input standing in front of the SmartBoard was the most efficient technique, followed by Semantic Snarfing. Laser pointer was the worst technique. Conditions other than the SmartBoard were performed seated about 1.52m away from the display.

In addition to the gyro-mouse, other physical input devices enable distant pointing in mid-air. The WorldCursor [35] uses a special wand and a laser projector that provides feedback about where the system thinks the user is pointing. Soap [5] wraps an optical sensor in a hull made of fabric. Relative motion of the hull enables both precise positioning of the cursor and moving across large distances. Zoom-and-pick [15] uses hand-held projectors to make accurate selections by locally distorting the region around the cursor. Foerenbach *et al.* [14] tried to enhance freehand pointing with tactile feedback but had limited success.

The Wiimote and other game controllers have also been studied as general-purpose pointing devices. Campbell *et al.* [10] evaluated the Wiimote operated as a zero-order or a first-order pointing device, finding that participants were roughly 2.5 times faster in the zero-order condition. Natapov *et al.* [25] compared remote pointing with a Wiimote, a classic gamepad's joystick, and a mouse operated on a desk serving as a baseline. They found that the mouse had the best throughput, followed by the Wiimote and the joystick. They report that hand tremor and small movements greatly affected accuracy in the Wiimote condition for small targets.

ARC-Pad [22] uses a touch-sensitive mobile device for cursor positioning on large displays. In absolute mode, the screen of the mobile device is mapped to the entire display, enabling coarse but fast repositioning of the cursor. In relative mode, input is interpreted as precise, relative adjustments to the cursor's position. With the Touch projector [8], users manipulate objects located on a distant display using an iPhone through a live video feed showing that display. As we will see later, given the small size and low input resolution of the touch-sensitive surface, ARC-Pad and the Touch projector do not offer enough precision for pointing on the ultra-high-resolution wall displays considered here.

The VisionWand [11] tracks the position of a wand in 3D using two low-cost cameras. While it does not improve distant pointing performance, it enables interactions such as tap, tilt, flip and rotate gestures. Nickel *et al.* [26] recognize pointing gestures with two cameras. They introduce new pointing techniques using information such as head and forearm orientation, but focus on gesture recognition rather than precision of pointing gestures. With Shadow Reaching [30], users reach distant objects through the shadow of their body cast on the display surface by a light source. Because of projection perspective, the regions that can be reached depend on both the setup and the user's distance to the display. Malik *et al.* [21] introduce another vision-based system for whole-hand gestural interactions performed on a constrained tabletop area. The system supports precise target acquisition on a back-projected wall-sized display from afar using asymmetric interactions, but is designed for people seated at a table.

Vogel and Balakrishnan [33] used a high-precision 3D motion tracking system to develop and evaluate three techniques: pure ray casting, relative pointing with clutching, and ray-to-relative pointing, which combines absolute and relative pointing using two different hand postures. We adapted the latter to our environment and tested it in *Exp. 2*.

Many techniques have been developed to facilitate pointing. Most are based on Fitts' law, an empirical model that predicts movement time (MT) as a function of movement amplitude (A) and target width (W) [31]:

$$MT = a + b \times log_2(A/W + 1) \qquad (1)$$

where a, b are determined empirically and depend on factors such as input device and user population. Pointing facilitation techniques attempt to decrease movement time either by reducing A, increasing W, or a combination of both. Except for Drag-and-pop [4] and the Vacuum [6], most pointing facilitation techniques have been designed for the desktop [2]. Since they often make few assumptions about the physical input device

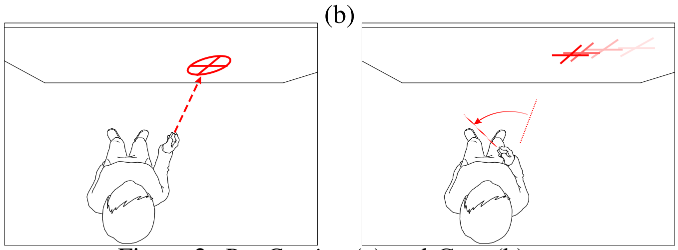

Figure 2: *RayCasting* (a) and *Gyro* (b).

used for pointing, they can be adapted to facilitate distant pointing. The present work focuses on generic, target-agnostic pointing techniques. Coupling them with efficient pointing facilitation techniques is beyond the scope of this paper, and should be the subject of future work.

3 The Limits of Modeless Techniques

Many devices can be used for remote pointing on wall displays. As for desktop pointing, some techniques map the absolute position of the input device to the cursor's position, while others use its relative motion to control cursor displacements. We first refined the set of candidate techniques and devices through pilot testing.

Techniques based on the absolute position of the input device include the family of *ray-casting* techniques. They extend the user's finger, or arm, or a hand-held device with an imaginary ray whose intersection with the wall display is highlighted (Fig. 2.a). Typical examples include laser pointers. Another absolute technique consists in holding a device at arm-length in front of the eyes so that the target is aligned with the tip of the device [29]. The technique is interesting as it resembles aiming, but informal tests quickly reveal its limitations: it is more tiring and less precise than laser pointing, it causes visual occlusion, and it requires users to repeatedly switch between two very different focal lengths.

Techniques mapping relative motion to cursor displacements can be based on position or rate control (zero or first order of control). Previous studies [10, 25] and our own tests revealed that techniques based on rate control allow for fast and comfortable coarse pointing across large distances, but perform poorly during the final precise pointing phase.

The set of candidate relative techniques and devices can be further refined by performing an analysis of the devices' characteristics using Casiez *et al.*'s formulae [12] to compute the control-display (CD) gains[1] of each technique. These formulae provide upper and lower bounds for the CD Gain based on the minimum target width of the tasks (W_{min}), the maximum distance between targets (A_{max}), the display resolution ($Sres$), the device's morphological characteristics —operating range (OR) and resolution ($Dres$)— and human motor precision ($Hres$).

$$CD_{min} = \frac{A_{max}}{OR} \qquad CD_{max} = \min(CD_{qmax}, CD_{lmax}) \quad \Bigg\| \quad CD_{qmax} = \frac{Dres}{Sres} \qquad CD_{lmax} = \frac{W_{min}}{Hres}$$

[1] Ratio between cursor movement and input device displacement.

Device	*Dres*	*OR*	*Hres*	CD_{min}	CD_{max}
Trackball	800 DPI	40 mm	.2 mm	5.5	0.1
Soap	800 DPI	35 mm	.2 mm	6.3	0.5
Trackpad	44 DPI	51 mm	.1 mm	13.8	4.6
GyroMouse	3638 px/rad	$\pi/2$ rad	.0031 rad	2.4	2.9

Table 1: Device characteristics for relative pointing techniques.

A gain below CD_{min} requires too much clutching to be efficient. A gain above CD_{max} creates precision problems because of hand tremor. If $CD_{min} > CD_{max}$, these problems are compounded. CD_{qmax} represents the maximum CD gain beyond which quantization problems start to occur, i.e., some pixels become unreachable. Using the original definition in the context of an ultra-high-resolution wall display yields very low values. We use a modified formula better adapted to our context, $CD_{qmax} = W_{min} \times Dres/Sres$, that guarantees that the smallest targets that we consider are reachable, but not necessarily every single pixel. Based on these formulae, we analyzed four devices (Table 1).

Soap [5] uses the tracking system of a mouse encased in a loose piece of fabric. Users control the cursor by moving the tracking system inside the fabric, like a piece of soap in the hand. The resolution is that of a regular mouse (600 to 800 DPI), but the operating range without clutching is much smaller (about 3.5 cm).

A *one-handed trackball* can be operated in mid-air. Its operating range is very small. The best commercial trackballs have a resolution of 1000 DPI and an operating range of approximately 4 cm.

A *handheld trackpad* can be implemented using a touch-sensitive device such as a PDA or smartphone. We tested an iPod Touch running a full-screen trackpad written with the MRMR iPhone App. Its resolution is 1000×1000 on a 51×76 mm surface.

A *GyroMouse* converts angular movements of a mouse held in mid-air into conventional mouse events. Users can clutch using a button that freezes the cursor. We used a Logitech MX Air (operating range $\approx \pi/2$ rad, constraint by the wrist).

In order to compute the CD_{min} and CD_{max} for each of the above, we had to define the corresponding *OR*, *Hres*, *Sres* and *Dres*. For the *Trackpad*, *Trackball* and *Soap*, we used Casiez *et al.*'s estimation for *Hres* (0.2 mm) and the devices' resolutions for *Dres* and *Sres*. Since *GyroMouse* uses angular movements as input, we adapted the formulae to obtain CD gains expressed in mm/rad. We used conservative values for the smallest target size (32 pixels or 7 mm) and largest amplitude (13800 pixels or 3187 mm). The display resolution *Sres* is 4.33 px/mm or 8658.82 px/rad at a distance of 2 meters.

Table 1 summarizes the results for relative devices. The first three have a CD_{min} much larger than their CD_{max}. They are therefore very likely to create too much clutching and/or precision problems. Had we taken more extreme values such as 10 pixels for smallest size and 20,000 pixels for largest amplitude, the differences would have been even more striking. We informally confirmed this assessment by trying various handheld trackballs and trackpads, concluding that only the gyroscopic mouse (Fig. 2.b) could be a candidate for this task.

4 Experiment 1: Limits of Modeless Techniques

The following formative user study was conducted to identify the limits of the two viable candidates identified above: an absolute technique, *RayCasting*, and a relative one, *Gyro*. We included two variants of the latter: the classic version with a fixed CD gain, and *GyroAcc*, which dynamically adjusts the CD gain according to input device velocity. We fine-tuned the sigmoid transfer function through pilot testing to obtain a smooth transition between the minimum and maximum gains.

4.1 Participants

Twelve unpaid volunteers (2 female) served in the experiment, aged 24 to 43 (mean 29.5, std dev. 5.76), all right-handed, with normal or corrected to normal vision. All participants were familiar with remote interaction, having used a WiiMote.

4.2 Apparatus

The wall-sized display (Figure 1) consists of 32 high-resolution 30" screens laid out in an 8×4 matrix. It is 5.5 meters wide and 1.8 meters high and can display 20480×6400 pixels. A cluster of 16 computers, each with two high-speed nVidia 8800GT graphics cards, communicate via a dedicated high-speed network through a front-end computer. A VICON motion-capture system tracks passive IR retroreflective markers and provides 3D object coordinates with sub-millimeter accuracy at 200Hz. The experiment was written in Java 1.5 running on Mac OS X and was implemented with the open source ZVTM toolkit modified to run on a computer cluster driving a wall-sized display. A recent study found no effect of bezels on pointing performance [7]. We chose to take into account the space behind bezels, making the cursor behave as if there were pixels under them.

All three techniques used an object tracked through the motion-capture system[2]. A wireless mouse was attached to it so that users could easily reach its left button to click. The maximum gain of *GyroAcc* was set so that users could move across the display without clutching. The minimum gain (0.32) was set to allow enough precision to acquire the smallest targets (see target WIDTH below) while being close enough to the maximum gain (10.6).

4.3 Task and Procedure

The task was a simple reciprocal pointing task. Participants were asked to click targets located alternatively left and right from the center of the display. Targets were presented as bright green disks on a black background. When the cursor was inside the target, the latter was highlighted white. An additional, wider green circle appeared, so that participants could see the feedback unambiguously even for very small targets. We required participants to dwell for 0.5 second before the target appeared so that the offsets between the hand-held device and the cursor in relative pointing conditions did not accumulate among trials, as this would have caused undesired clutching. This dwell zone was a 500-pixel-wide circular area centered on the previous target. Dwell zones disappeared at the end of the dwell time, signaling the start of the trial. Participants stood at a distance of 2 meters from the display. This distance gave participants a good overview of the display while avoiding problems of visual acuity[3].

In this formative study, we were mainly interested in evaluating the limits of the three considered techniques in terms of precision. We thus always presented targets

[2]We implemented the gyroscopic mouse by tracking the angular movements of a passive object. This gave us full control over pointer acceleration whereas both the operating system and the Logitech MX Air device driver feature native pointer acceleration functions that could neither be canceled nor finely tuned.

[3]Point acuity (1' of arc, [34]) and min decipherable symbol height (5' of arc, [33]) suggest that we are above the threshold, with smallest targets at 12.7' of arc and 6.35' of arc in our two experiments.

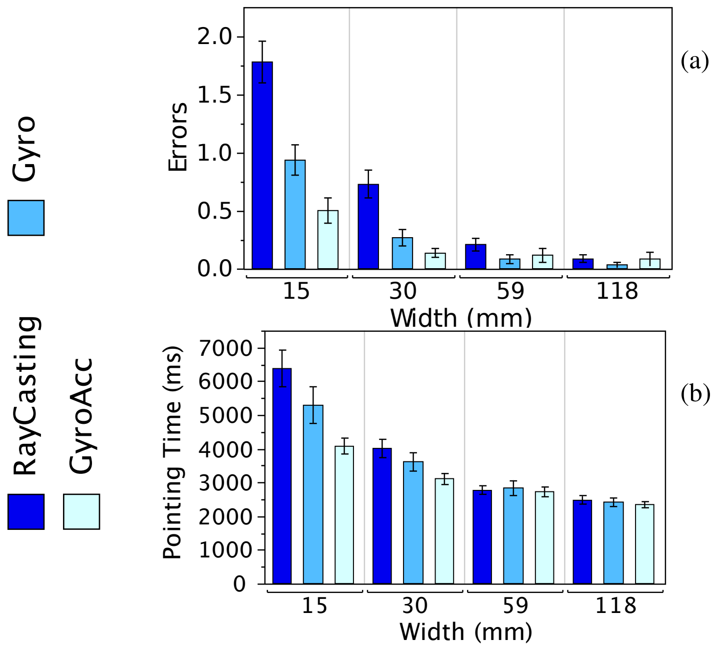

Figure 3: (a) *Errors* and (b) *Pointing Time* per TECHNIQUE × WIDTH.

of decreasing width, stopping the experiment for each technique on a per-participant basis: if a given target was not selected after ten seconds, the trial timed out. When four successive *TimeOuts* occurred (*Withdrawal*), we considered the task too difficult for the current TECHNIQUE and switched to the next technique, resetting WIDTH to the largest size. The distance between targets was fixed at 3187 mm.

The main factors were TECHNIQUE (*RayCasting*, *Gyro*, *GyroAcc*) and target WIDTH ($118, 59, 30, 15, 7$ mm). We checked that participants could indeed see targets of all WIDTHS. We used a 3×5 repeated measures within-subject design with 10 replications, i.e. 1800 trials ($3 \times 5 \times 10 \times 12$ participants). For each participant, we grouped trials into 15 blocks (TECHNIQUE × WIDTH). The presentation order for TECHNIQUE was counterbalanced across participants using a Latin square. For each technique, participants were asked to practice using 118 mm targets until they felt comfortable with it before starting actual measurements. A trial started as soon as the dwell phase ended. For each trial, we logged the time to click the target (*Pointing Time*) and the number of clicks outside the target (*Outside Clicks*).

4.4 Results

We analyzed the data using multiway ANOVAs, accounting for repeated measures using the REML procedure, and performed Tukey HSD post-hoc tests for pairwise comparisons. We took the median for *Pointing Time* data and the mean for *Errors*. We verified that there was no effect of TECHNIQUE presentation order and observed that learning and fatigue effects were not significant. We now report the results relevant to assessing the limits of each technique, i.e., task time and mean number of errors (Fig. 3)[4].

[4]Error bars in all the figures represent the 95% confidence limit of the mean of the medians per participants ($\pm StdErr \times 1.96$).

Timeouts and Withdrawal We observed no *Withdrawal* for WIDTH > 15. Only *RayCasting* caused *Withdrawal*s for WIDTH $= 15$ (mean 5.83%). For WIDTH $= 7$, *GyroAcc*, *Gyro* and *RayCasting* caused 1.67%, 14.17% and 47.5% *Withdrawal*s, respectively. WIDTH$=7$ was too difficult for *RayCasting* and *Gyro*. We removed the corresponding blocks from all subsequent analyses.

In the remaining blocks, we observe significant effects on *TimeOuts* for TECHNIQUE ($F_{2,20.92} = 4.46$, $p < .025$), WIDTH ($F_{3,31.62} = 10.84$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{6,61.1} = 7.03$, $p < 0.0001$). *GyroAcc* (mean 1%) causes significantly fewer *TimeOuts* than *RayCasting* (6%), *Gyro* being in between. Significantly more *TimeOuts* are observed at WIDTH $= 15$ mm (mean 12%) than 30 mm (mean 1%), 59 mm (1%) and 118 mm (no *TimeOuts*). For WIDTH $= 15$ mm, *GyroAcc* (mean 2%) causes significantly fewer *TimeOuts* than *Gyro* (13%) and *RayCasting* (22%).

Errors Trials with one or more *Outside Clicks* were treated as errors. We observe a significant effect on *Errors* for TECHNIQUE ($F_{2,22} = 40.38$, $p < 0.0001$), WIDTH ($F_{3,33} = 90.64$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{6,66} = 15.42$, $p < 0.0001$). Unsurprisingly, *Errors* increase significantly as WIDTH decreases, except for $Width = 59$ mm and $Width = 118$ mm (Fig. 3-a). The interaction does not change the significance of the post-hoc test, but indicates that the magnitude of the difference increases as target WIDTH decreases. For $Width = 15$ mm, *RayCasting* (mean 1.78) causes significantly more *Errors* than *Gyro* (.93) which causes significantly more *Errors* than *GyroAcc* (.5).

Pointing Time We observe a significant effect on *Pointing Time* for TECHNIQUE ($F_{2,22} = 15.17$, $p < 0.0001$), WIDTH ($F_{3,33} = 59.59$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{6,66} = 16.36$, $p < 0.0001$). *GyroAcc* (mean 3061 ms) is significantly faster than *Gyro* (3537 ms) and *RayCasting* (3902 ms). Unsurprisingly, *Pointing Time* increases significantly when WIDTH decreases (Fig. 3-b), and the interaction does not change the significance of the post-hoc test, but indicates that the magnitude of the difference increases as target WIDTH decreases.

4.5 Discussion

The above results show that *Pointing Time*, *Errors* and *TimeOuts* correlate well. *RayCasting* is not accurate enough to select targets such as those found on a map displayed on an ultra-high-resolution wall (Figure 1): Due to hand tremor and input resolution, the accuracy of this technique makes it difficult to acquire targets smaller than 30 mm (128 px) at a distance of 2 meters from the display. Relative techniques such as a *Gyro* mouse can be made precise enough by choosing a sufficiently low CD gain, making it possible to acquire targets 15 mm wide. However, the high number of *TimeOuts* (12%) shows that it is not really usable for such widths with a 3-meter amplitude. *GyroAcc* alleviates this problem by dynamically adjusting the CD gain as a function of input device velocity, allowing users to control the tradeoff between speed and precision. It can be made efficient for pointing targets that are both distant and small. *GyroAcc* was precise enough to acquire the smallest targets (7 mm), while fast enough to move across more than 3 m. While *GyroAcc* performed relatively well, *Withdrawal* also started to appear for 7 mm targets, suggesting that it is reaching its limits at that size. Furthermore, for higher differences between A_{max} and W_{min}, the min and max cursor gains will become too different and the much steeper transfer function will become hard to control.

5 Dual-precision Techniques

Having established the limits of single-mode techniques, we now turn to dual-precision techniques. Dual-precision pointing techniques feature two modes: a coarse mode that allows for fast movements to easily reach distant targets with no or little clutching, and a a precise mode for acquiring small targets.

5.1 Key Parameters

The design of dual-precision techniques relies on three key parameters: the gain used in each phase and the point at which the user is expected to switch mode. In order to be optimal, the mode switch should occur when the target is within the operating range of the precise mode, which we denote L. To assist users, we propose to visually represent this limited operating range by surrounding the cursor with a circle of diameter L when in coarse pointing mode. The coarse pointing phase can then be seen as an area cursor pointing task, consisting in bringing the cursor's circle over the target, while the precise pointing phase is a regular target acquisition task with a distance $d \leq L/2$.

The difficulty of each phase is $log(1+A/L)$ and $log(1+L/2W)$ respectively (A is the amplitude). If we assume that the throughput is the same in both phases, pointing time will be optimal if both phases have the same difficulty, i.e.:

$$\frac{A}{L} = \frac{L}{2W} \iff L = \sqrt{2AW} \tag{2}$$

Using worst-case values ($W = W_{min}$ and $A = A_{max}$), equation (2) becomes:

$$L^* = \sqrt{2A_{max}W_{min}} \tag{3}$$

Equation (3) gives the ideal value for L. Casiez *et al.*'s formulae, with the modification introduced earlier, allow us to compute bounds for L (subscripts $_P$ and $_C$ indicate values for the precise and coarse techniques, respectively):

$$L < 2OR_P \times \min\left(\frac{W_{min} \times Dres_P}{Sres}, \frac{W_{min}}{Hres_P}\right) \tag{4}$$

$$L > \frac{A_{max} \times Hres_C}{OR_C} \tag{5}$$

In the coarse pointing phase, the goal is to cover the amplitude A as fast as possible. Users should be able to cover A_{max} in a single gesture, i.e., within the operating range OR_C. In the precise pointing phase, the target is at a distance smaller or equal to L. This distance should be reachable within OR_P. The optimal CD gains for coarse and precise mode are thus:

$$CD_C^* = \frac{A_{max}}{OR_C} \quad (6) \qquad\qquad CD_P^* = \frac{L}{OR_P} \quad (7)$$

For a given technique, Equations (3), (6) and (7) give the key parameters, while Equations (4) and (5) allow us to test that the dual-mode technique match the constraints for the task.

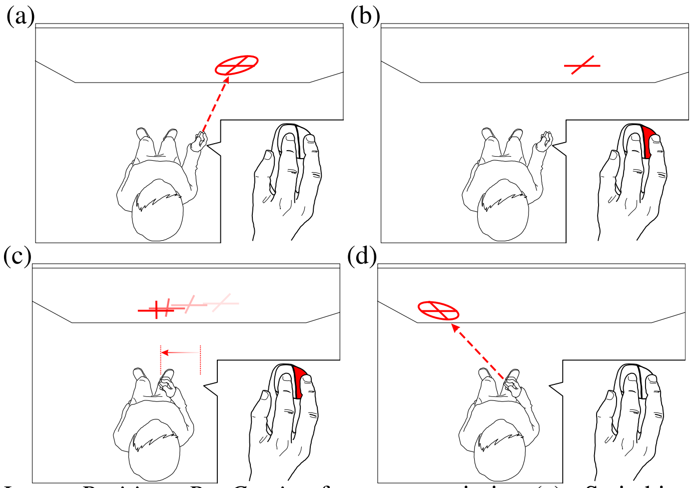

Figure 4: *Laser+Position*. *RayCasting* for coarse pointing (a). Switching to precise mode by pressing a button (b). Relative translational movements control cursor movements (c). Switching back to coarse mode by releasing the button (d). Click performed with left button.

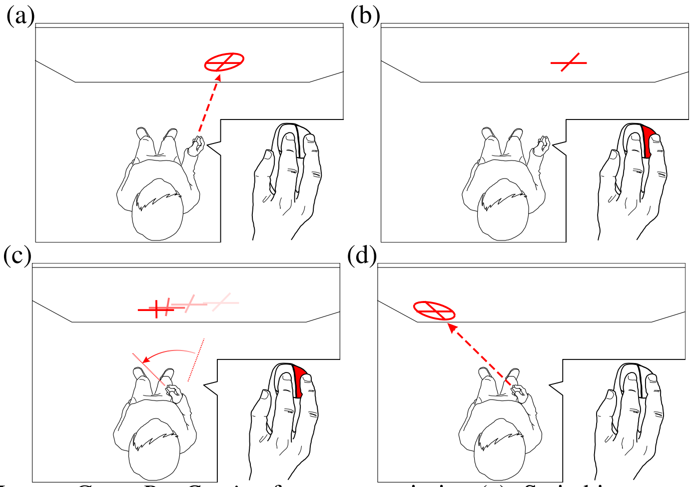

Figure 5: *Laser+Gyro*. *RayCasting* for coarse pointing (a). Switching to precise mode by pressing a button (b). Relative rotational movements control cursor movements (c). Switching back to coarse mode by releasing the button (d). Click performed with left button.

5.2 Techniques

Pointing is an elementary task that will be combined with other actions in a real context of use. Techniques that enable high-precision pointing should therefore be *eye-free* and *single-handed*. The rationale is that eye-free techniques do not require users to divide their attention, unlike, e.g., Semantic Snarfing [23] and to a lesser extent, ARC-Pad [22]. In addition, single-handed techniques are more likely to minimize fatigue due to uncomfortable hand/arm postures and facilitate a variety of tasks, such as holding a document in the other hand while pointing.

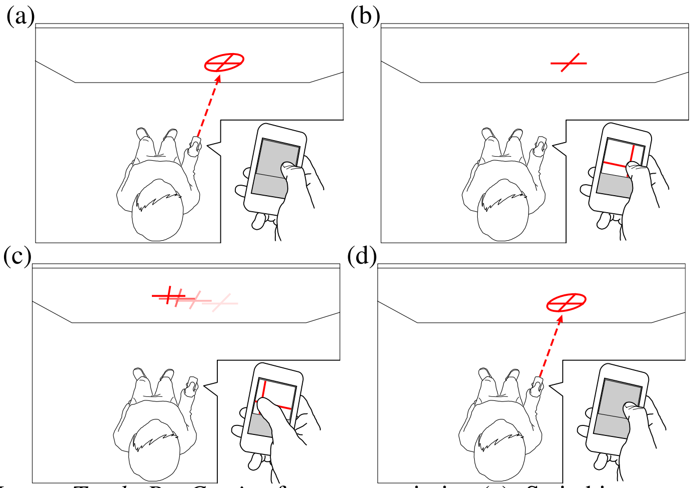

Figure 6: *Laser+Track*. *RayCasting* for coarse pointing (a). Switching to precise mode by touching the surface (b). Controlling cursor movements by moving the thumb (c). Switching back to coarse mode by releasing the thumb (d).

In the following experiment, we compare the most efficient technique from our formative experiment, *GyroAcc*, to three techniques that use an explicit mode switch to transition from coarse to precise pointing mode. All three techniques use *RayCasting* as their coarse mode, because it is known to be intuitive and does not require clutching.

Laser+Position (Fig. 4) is an adaptation of Vogel's free-hand *RayToRelative* technique [33]. Instead of detecting hand gestures for mode switching and clicking, we use the buttons of a wireless mouse. *Laser+Position* combines *RayCasting* for coarse pointing and relative translational movements for precise pointing. In relative mode, translations are taken into account in a plane orthogonal to the current orientation of the hand-held device. Precise pointing is activated by keeping a button depressed. A second button is used for clicking. Users can clutch in precise mode by releasing the first button and repositioning their hand. If they press the first button again within less than 600 ms (tuned through pilot testing), the technique doesn't switch back to coarse mode.

Laser+Gyro (Fig. 5) combines *RayCasting* for coarse pointing and relative rotational movements for precise pointing. Compared to *Laser+Position*, which mainly involves upper limb segments (forearm up to shoulder) in relative mode, *Laser+Gyro* mainly involves the wrist and is potentially less tiring. Clutching, clicking and mode switching are identical to the *Laser+Position* technique.

Laser+Track (Fig. 6) combines *RayCasting* for coarse pointing and relative translational movements of the thumb on a touch-sensitive surface (PDA, smartphone, etc.) for precise pointing. The surface is divided into two areas: an upper zone (1) for tracking and a lower (smaller) zone (2) for clicking. Switching between the two zones can be done easily using proprioceptive information and does not require the user to look at the device. Touching zone 1 switches to precise mode. Switching back to coarse mode only happens 300 ms (tuned through pilot testing) after the thumb has been released, thus enabling clutching. This clutch timer is reset each time a click occurs, so that users can stay in precise mode if the click was a miss. To compensate for unintended finger movements at release time, we retrieve the click point coordinates 200 ms before the finger-up event.

For all three techniques, the cursor is a crosshair surrounded by a circle (Fig. 4-6). The circle's diameter is equal to the value of L for that technique. In precise mode, the circle is decoupled from the crosshair and displayed as a ghost at the position where the cursor will be when the user switches back to coarse mode. This is because coarse mode is absolute and the cursor jumps when transitioning back from precise mode. The opacity of the ghost is inversely proportional to its distance to the crosshair so as to minimize visual interference, with a maximum value of 25%.

6 Experiment 2: Dual-Precision Techniques

6.1 Participants, Apparatus and Task

The 12 participants of *Exp. 1* served in *Exp. 2*, with at least a two-day interval between the two.

RayCasting was implemented as in *Exp. 1* using the VICON motion tracker. Both *Laser+Gyro* and *Laser+Position* used a wireless mouse which was attached to the tracked object. The right button was used for mode switching and clutching, the left button for clicking. A mouse was also used for *GyroAcc*: the right button was used for clutching and the left button for clicking. *Laser+Track* used an Apple iPod Touch as a touch-sensitive surface.

For the three dual-mode techniques, L was computed using equation (3): $L = 154$ mm. It was within the range defined by equations (4) and (5) (limit cases). The CD gain of each precise mode was computed using equation (7): $CD_P = 3.07$ for *Laser+Track*, 0.51 for *Laser+Position* and 0.15 for *Laser+Gyro*. The maximum and minimum CD gain for *GyroAcc* were computed using equations (6) and (7): 5.31 and 0.25.

The main factors were TECHNIQUE, AMPLITUDE and target WIDTH. The values of WIDTH were 30, 15, 7 and 4 mm. We checked that participants could actually see all the targets. The values of AMPLITUDE were 637, 1912 and 3187 mm. We used a $4 \times 4 \times 3$ repeated measures within-subject design with three independent variables. For each participant, we grouped trials into 48 blocks, one per TECHNIQUE, AMPLITUDE and WIDTH. The presentation order for TECHNIQUE, AMPLITUDE and WIDTH was counterbalanced across participants using a Latin square. Each time a new TECHNIQUE began, participants had the opportunity to train with $Amplitude = 1912$ mm and $Width = 7$ mm. The actual trials started when the participant felt ready and her pointing time stabilized, i.e., the task time difference between the slowest and fastest trials among the last four had to be within 30% of the mean of these trials.

To summarize, we collected 4 TECHNIQUE $\times$ 4 WIDTH $\times$ 3 AMPLITUDE $\times$ 5 replications $\times$ 12 participants = 2880 trials. The task was the same as in *Exp. 1*. For each trial, in addition to *Outside Clicks* and *Pointing Time*, we logged the time to acquire the dwell zone (*Recalibration*), the time to reach the target (*Reaching*), the time to perform the first click (*Clicking*) and target *Crossings*.

At the end of the experiment, participants were asked to rank the techniques and rate them for *Mental Effort*, *Accuracy*, *Speed*, *Fatigue*, *Comfort* and *Overall Easiness* on 5-point Likert scales.

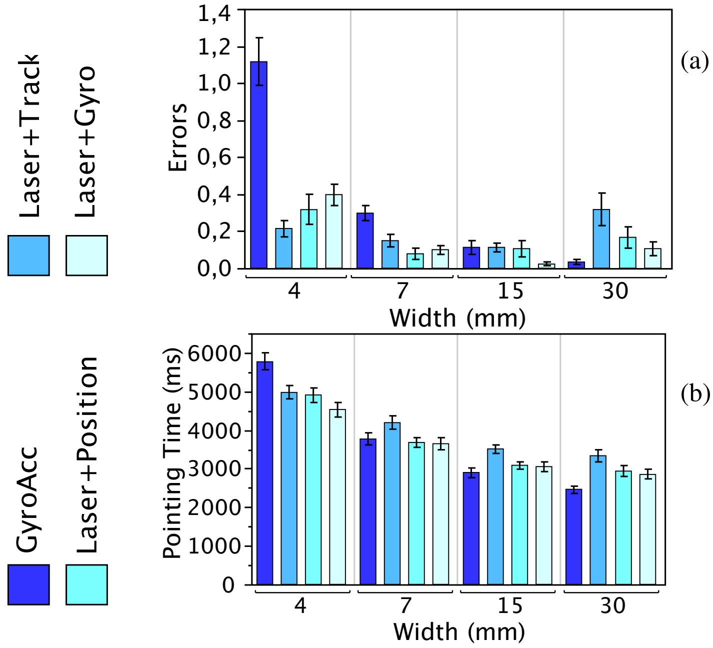

Figure 7: *Pointing Time* and *Errors* by TECHNIQUE.

6.2 Predictions

The precise modes of *Laser+Gyro* and *Laser+Position* are similar and are controlled by the same limbs (forearm, wrist and hand). We expect them to have similar performance (prediction *P1*). However, *Laser+Position* should be more tiring since rotations are controlled more naturally than translations (prediction *P2*). *Laser+Track* is the only dual-mode technique whose precise mode does not require moving the hand-held device, so we expect it to be faster for *Recalibration* (prediction *P3*). The minimum gain for *GyroAcc*'s transfer function had to be lowered compared with *Exp. 1* because the targets are smaller. This should negatively affect its performance (*P4*).

6.3 Results

We analyzed the data using multiway ANOVAs, accounting for repeated measures using the REML procedure, and performed Tukey HSD post-hoc tests for pairwise comparisons. We took the median for *Pointing Time* data and the mean for *Errors* and *Crossings*. We verified that there was no effect of TECHNIQUE presentation order and observed that learning and fatigue effects were not significant. All reported results are significant at least at the $p < 0.001$ level unless noted otherwise.

Timeouts 3% of the trials were *TimeOuts*. There is a significant effect on the amount of *TimeOuts* for TECHNIQUE ($F_{3,33} = 13.63$, $p < 0.0001$), AMPLITUDE ($F_{2,22} = 4.67$, $p = 0.0204$), WIDTH ($F_{3,33} = 25.44$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{9,99} = 8.44$, $p < 0.0001$). As expected, larger amplitudes and smaller widths cause more *Errors*. *Laser+Track* (mean 0.06) and *GyroAcc* (0.04) cause significantly more *TimeOuts* than *Laser+Position* (0.01) and *Laser+Gyro* (0); the effect increases with smaller widths.

Errors For this analysis we considered that each *Outside Click* was an error (Fig. 7-a). There is a significant effect on *Errors* for TECHNIQUE ($F_{3,33} = 13.19$, $p < 0.0001$), WIDTH ($F_{3,33} = 43.21$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{9,99} = 15.47$, $p < 0.0001$). As expected, *Errors* increased with smaller widths. *GyroAcc* (mean 0.44) causes significantly more *Errors* than the other techniques (means from 0.16 to 0.26). The effect was even stronger with $Width = 4$ mm (mean 1.36).

Crossings There is a significant effect on *Crossings* for TECHNIQUE ($F_{3,33} = 19.57$, $p < 0.0001$), AMPLITUDE ($F_{2,22} = 3.48$, $p = 0.0488$), WIDTH ($F_{3,33} = 79.66$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{9,99} = 19.9$, $p < 0.0001$). As expected, smaller widths cause more crossings. The effect of AMPLITUDE is a bit surprising, with more *Crossings* for the medium amplitude. *GyroAcc* and *Laser+Track* (resp. 1.13 and 1.03) cause significantly more *Crossings* than *Laser+Position* and *Laser+Gyro* (resp. 0.7 and 0.61). *GyroAcc* causes almost twice as many *Crossings* than the second worst condition for $Width = 4$ mm.

Dwell Time There is a significant effect on *Recalibration* for TECHNIQUE ($F_{3,33} = 7.35$, $p = 0.0007$), AMPLITUDE ($F_{2,22} = 65.42$, $p < 0.0001$), WIDTH ($F_{3,33} = 10.42$, $p < 0.0001$), TECHNIQUE×AMPLITUDE ($F_{6,66} = 3.83$, $p = 0.0024$) and AMPLITUDE×WIDTH ($F_{6,66} = 3.87$, $p = 0.0023$). As expected, *Recalibration* increases with AMPLITUDE. Recalibration takes significantly more time with *GyroAcc* (mean 1722 ms) than with all other techniques (1504 ms to 1417 ms), especially for the larger AMPLITUDES.

Reaching Time We found a significant effect on *Reaching* for TECHNIQUE ($F_{3,33} = 3.65$, $p = 0.022$), WIDTH ($F_{3,33} = 308.06$, $p < 0.0001$) and AMPLITUDE ($F_{2,22} = 134.3$, $p < 0.0001$). As expected reaching time increases with task difficulty. *Laser+Track* (mean 2710 ms) is significantly slower to reach the target than *GyroAcc* (2428 ms), with the other two techniques in between.

Pointing Time There is a significant effect on *Pointing Time* for TECHNIQUE ($F_{3,33} = 13.09$, $p < 0.0001$), AMPLITUDE ($F_{2,22} = 71.14$, $p < 0.0001$), WIDTH ($F_{3,33} = 140.52$, $p < 0.0001$) and TECHNIQUE×WIDTH ($F_{9,99} = 8.56$, $p < 0.0001$). As expected, pointing time increases with task difficulty. *Laser+Track* (mean 4268 ms) is significantly slower than the other techniques (means from 3519 to 3847 ms). For $Width = 4$ mm, *GyroAcc* is the slowest.

6.4 Modelling Pointing Time

As described earlier, the task of pointing with a dual-mode technique consists of two phases, coarse and precise, with a mode switch in between. We expect the movement time of each pointing phase (MT_C and MT_P) to follow Fitts' law and assume that the mode switch takes a constant time MT_S dependent on the technique. We obtain the following model for the global pointing task time (MT_T):

$$
\begin{aligned}
MT_T &= MT_C + MT_S + MT_P && (8)\\
&= (a_c + MT_S + a_p) + b_c \, log\left(1 + \frac{A}{L}\right) + b_p \, log\left(1 + \frac{d}{W}\right) && (9)\\
&= a + b_c \, ID_C + b_p \, ID_P && (10)
\end{aligned}
$$

In order to assess our model, we removed all trials with no mode switch (28.6%, mostly for $Width = 30$ mm). Using $d = L/8$ as a conservative value for the amplitude of the second pointing phase, we obtain:

$$\begin{aligned} \textit{Laser+Gyro}: &\quad 367 + 486 \times ID_C + 791 \times ID_P \\ \textit{Laser+Position}: &\quad 329 + 437 \times ID_C + 960 \times ID_P \\ \textit{Laser+Track}: &\quad 968 + 377 \times ID_C + 937 \times ID_P \end{aligned}$$

The goodness of fit ($r^2 = .97$, .94 and .94 respectively for *Laser+Gyro*, *Laser+Position* and *Laser+Track*) is better than when modeling the global task time with Fitts' law ($r^2 = .93$, .84 and .82). The constants in the above regressions confirm that *Laser+Gyro* and *Laser+Position* are very similar (prediction *P1*), with a slight advantage for *Laser+Gyro* in the precise phase. It also supports the fact that *Laser+Track* is penalized by its precise mode. Since b_p is consistently higher than b_c, users seemed to have more difficulty with the precise mode, maybe due to mental readjustment caused by the change of input modality from coarse to precise.

6.5 Qualitative results

A Pearson χ^2 test shows that there is a significant effect on *Mental Effort*, *Accuracy*, *Comfort*, *Easiness* and *Ranking* for TECHNIQUE. 6 participants graded mental effort for *Laser+Track* as *High* or *Too high*, and all 12 graded all other techniques *Normal* (3) or below. 6 participants graded precise pointing with *Laser+Track* and *GyroAcc* as *Difficult* or *Very difficult* and 9 graded it *Easy* or *Very easy* with *Laser+Gyro* and *Laser+Position*.

10 participants graded *Laser+Track Uncomfortable* or *Very uncomfortable*. 10 and 7 participants respectively graded *Laser+Gyro* and *Laser+Position* as *Comfortable* or *Very comfortable*, partially supporting prediction *P2*. 10 participants graded *Laser+Position* and *Laser+Gyro* as *Easy* or *Very easy* and 10 graded *Laser+Track* as *Normal* (3) or below. Finally, 8 participants preferred *Laser+Gyro* overall, 2 preferred *Laser+Position*, 2 preferred *GyroAcc* and none preferred *Laser+Track*. Overall, these results are consistent with the quantitative analysis.

6.6 Discussion

GyroAcc was generally perceived as imprecise, which is consistent with the quantitative results, especially for very small targets. It was also the worst for *Recalibration*, i.e., the offset between the hand-held device and the cursor often became quite large. This means that in real situations users will probably have to clutch often. However it was the fastest technique for reaching targets, contradicting prediction *P4*. This indicates that mode-switching takes significant time. From both the quantitative and qualitative results, we suggest that *GyroAcc* be used when targets are always larger than 7 mm.

Laser+Track was not better for recalibration time, contradicting prediction *P3*. In fact it was among the slowest techniques. It caused many *Crossings* and was the slowest for *Reaching*, meaning that the precise mode is neither precise nor fast enough to compete with other dual-mode techniques. This is also consistent with the participants' opinion: hard to use, imprecise and uncomfortable. Part of this may be due to the following problem: 5 participants reported that clicking caused a loss of precision despite our finger-release adjustment and would have preferred a physical button.

Laser+Gyro and *Laser+Position* had very similar results, supporting prediction *P1*. They were easy to control and were the fastest techniques. However, *Laser+Gyro* was

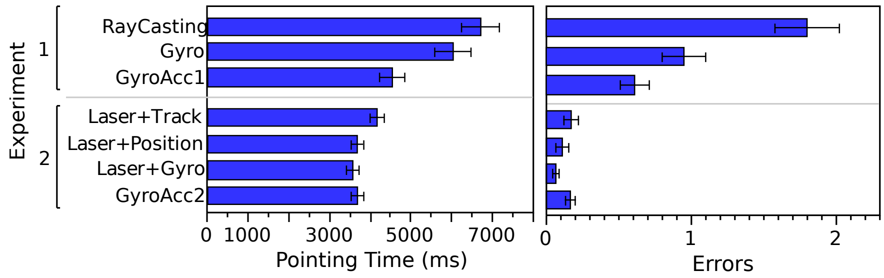

Figure 8: *Pointing Time* (a) and *Errors* (b) for all TECHNIQUES.

the most preferred technique and had a slight advantage in terms of pointing very small targets, consistent with prediction *P2*.

6.7 Comparing single- and dual-mode techniques

We compared the techniques in *Exp. 1* and *Exp. 2* for *Pointing Time* and *Errors* for the conditions common to the two experiments: $Amplitude = 3187$ mm and $Width \in \{7, 15, 30\}$ mm. For both measures we found a significant effect ($p < 0.0001$) of TECHNIQUE, WIDTH and TECHNIQUE×WIDTH. Measures for *GyroAcc* are reported separately as *GyroAcc1* for *Exp. 1* and *GyroAcc2* for *Exp. 2* because the more challenging conditions in *Exp. 2* called for different acceleration settings in order to make smaller targets reachable.

As expected, *Errors* and *Pointing Time* increase significantly when WIDTH decreases. As shown in Fig. 8.a, *RayCasting* and *Gyro* are significantly slower than all other techniques (means 6846 and 6018 ms). The next slowest technique is *GyroAcc1* (4527 *ms*), although *Laser+Track* (4152 ms) is not statistically different from it and from the remaining techniques. The pattern for errors is similar (Fig. 8.b). *RayCasting* (mean 1.84) causes the most errors, and *Gyro* and *GyroAcc1* (means .95 and .61) cause significantly more errors than the techniques in *Exp. 2*. For $Width = 7$ mm, the techniques in *Exp. 1* significantly underperform those in *Exp. 2* for both time and error. For $Width = 15$ mm, *RayCasting* and *Gyro* significantly underperform all other techniques.

These results show that are either absolute or that use static gains are less efficient than dual-mode techniques or those using dynamic gains, even for easily reachable targets. It may be surprising that dual-mode techniques with an explicit mode-switch perform better than *RayCasting* or *GyroAcc* for $Width = 30$ mm since *Exp. 1* showed that *RayCasting* had enough precision to reach those targets. Based on the error rates of both experiments and on the *Crossings* measured in *Exp. 2*, we suggest that switching to the precise mode makes the click more stable: it reduces the impact of the tremor caused by clicking as well as the crossings and clicks outside the target.

7 Conclusion and Future Work

We investigated the problem of pointing on large ultra-high-resolution (100 dpi) wall displays from a distance. We first explored the limits of existing modeless remote pointing techniques, both absolute and relative. We showed that targets smaller than 30 mm (128 px) could not be reached reliably with a 3m amplitude if a single static CD gain was used, as a low gain would require too much clutching to cross large distances. With a dynamic gain, the practical limit improved to about half this size.

We then investigated dual-precision techniques that combine a coarse and a precise pointing mode. We introduced a model for predicting pointing time, a method to calibrate them and computed theoretical limits for their usage. We compared the performance, error rate and user preference of three dual-precision techniques, showing that targets as small as 4 mm (16 px) can be acquired reliably when standing 2 meters away from the display. In comparison, the smallest targets studied in previous work were at least four times as large. Our results show that dual-mode techniques perform better than classic techniques for targets smaller than 30 mm (15 mm for *GyroAcc*), and that a good precise mode is crucial for both performance and user acceptance. The best techniques combined ray-casting with either device rotational (*Laser+Gyro*) or translational (*Laser+Position*) movements in precise mode, with a slight participant preference for *Laser+Position*. The combination of ray-casting and a hand-held trackpad was the least preferred.

Our future work includes improving clicking with *Laser+Track* and using pointer acceleration in dual-mode techniques to increase performance and ease of use. We will also study these techniques in combination with other common interactions such as navigation and menu selection to better assess their ecological validity.

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