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Handheld Augmented Reality: Effect of registration jitter on cursor-based pointing techniques

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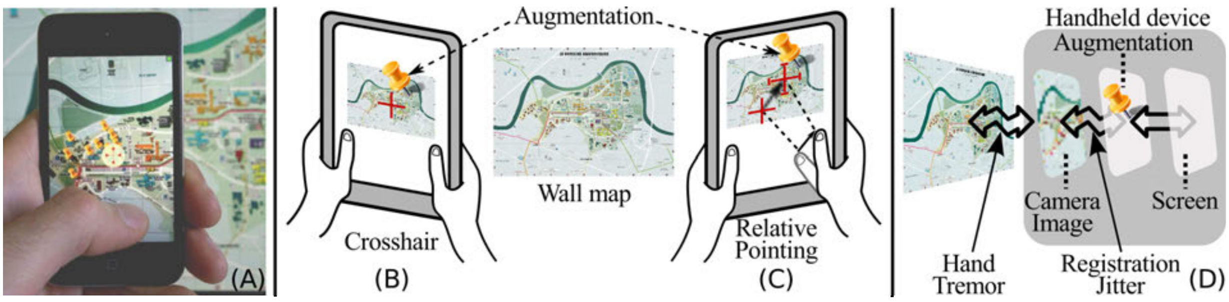

Figure 1. Handheld AR cursor-based pointing: (A) Pointing at digital marks on a physical wall map; (B) Screen-centered crosshair pointing; (C) Relative pointing with cursor stabilized in the physical object's (image) frame. (D) Spatial relations of the on-screen content in handheld AR.

ABSTRACT
Handheld Augmented Reality relies on the registration of digital content on physical objects. Yet, the accuracy of this registration depends on environmental conditions. It is therefore important to study the impact of registration jitter on interaction and in particular on pointing at augmented objects where precision may be required. We present an experiment that compares the effect of registration jitter on the following two pointing techniques: (1) screen-centered crosshair pointing; and (2) relative pointing with a cursor bound to the physical object's frame of reference and controlled by indirect relative touch strokes on the screen. The experiment considered both tablet and smartphone form factors. Results indicate that relative pointing in the frame of the physical object is less error prone and is less subject to registration jitter than screen-centered crosshair pointing.

Keywords
Handheld Augmented Reality; Pointing Technique; Jitter.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces – Evaluation/methodology, input devices and strategies.

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INTRODUCTION
Augmented Reality (AR) relies on the registration (i.e., the alignment) of the digital content -the "augmentation"- on the physical surrounding (e.g., digital marks registered with a wall map as in Figure 1). For the case of handheld AR, the physical surrounding is represented on the screen by the live image of the back-face camera. Moreover the camera image representing the physical surrounding as well as the digital augmentation are displayed simultaneously on the screen. Thus, handheld AR relies on the spatial relation between the physical surrounding and the on-screen content (i.e., the camera image and the augmentation) (Figure 1-D).

Different factors can impair the stability of this spatial relation. First, as the handheld device is not self-stabilized, its position and orientation are subject to natural hand tremor. The device's position and orientation usually control the viewpoint of the camera, which is therefore not stable. As a consequence, the on-screen content (both the live camera image and the augmentation) is not stable on the screen (Figure 1-D). Second, the registration of the augmented content on the camera image relies on the system's knowledge of the position of the camera in the physical surrounding. This knowledge is typically gathered by a tracking system (e.g., external motion capture system or computer-vision analysis of the camera images). The accuracy of this underlying tracking system depends on the environment. For example, vision-based tracking accuracy can depend on lighting conditions or on the availability of feature points to track. Poor tracking conditions can result in a jittery registration of the augmentation.

On the one hand, hand tremor affects the viewpoint on the augmented scene. On the other hand, registration jitter affects the spatial relation between the camera image and the augmentation (Figure 1-D). Both hand tremor and registration jitter can impair the legibility of the augmented content and of its relation with the physical surrounding. This can also impair the user interaction with the augmented scene.

In particular, hand tremor and registration jitter can impair the accuracy of pointing at the augmented content (e.g., augmented items on a wall map as in Figure 1). With handheld AR systems, pointing at targets is performed in two phases: (1) A physical pointing phase, which points the camera towards the target in space; and (2) a virtual pointing phase, which points at the target through the live camera image [12]. In this paper, we evaluate the sensitivity to registration jitter and to device form factor of the following two cursor-based pointing techniques for pointing adjustment during the virtual pointing phase:

- Using a screen-centered *crosshair* (Figure 1-B) as studied by Rohs et al. [12][13]. This technique performs an absolute pointing in space. As the cursor is bound to the handheld device screen, the pointing accuracy of this technique should be impaired by both hand tremor and registration jitter.

- Using *Relative Pointing* [16]. The cursor is bound to the physical object rather than to the handheld device screen (Figure 1-C). Finger strokes on the screen control the cursor displacement in an indirect and relative way. The cursor remains visible on the screen at all times. Indeed the cursor is automatically moved in case a change in the camera's viewpoint or a finger motion would otherwise make the cursor invisible on the screen. Since the cursor as well as the digital augmentation are registered with the physical object, the accuracy of this technique when pointing at digital targets should not be impaired by registration jitter.

We held a controlled experiment comparing those two techniques under two conditions of registration jitter on both touch-based handheld phone and tablet form factors. Our results indicate that *Relative Pointing* is overall more accurate and is also less sensitive to both registration jitter and device form factor than *Crosshair*.

In this paper, we first review related work before reporting the experiment. We conclude with a discussion of our results and directions for future work.

RELATED WORK

We build on previous work on handheld AR pointing techniques as well as on studies of the impact of registration errors on user interaction.

Handheld AR pointing

Acquiring targets in handheld AR is commonly performed with either a screen-centered *crosshair* (e.g., [12][13]) or by direct input on the screen, using a pen or bare fingers (e.g., [2]). Rohs et al. [12][13] modeled *crosshair* pointing with a two parts Fitts law. As explained above, they considered two phases: (1) physical pointing where the target is not visible on the screen but observable directly in the surrounding environment; and (2) virtual pointing where the target is seen through the live camera image. In *Touch Projector* [2], Boring et al. proposed to move pictures on a remote screen by manipulating them through the live camera image of a handheld device. To improve the user interaction, they used both manual and automatic zooming as well as freeze-frame (i.e., pausing the live camera image). In [16], we proposed two pointing techniques for handheld AR: (1) combining *Shift* [17], a touch-based handheld device pointing technique, with freeze-frame, and (2) extending the *crosshair* technique with a *relative pointing* mode where the cursor is stabilized on a physical wall map and controlled with finger strokes on the touch screen. The experiments indicated that those two techniques, *Shift&Freeze* and *Relative Pointing*, were preferred by users and were more accurate but longer to operate than both *crosshair* and direct touch. In this paper, we further compare the use of *crosshair* and *Relative Pointing* for pointing adjustment during the virtual pointing phase (i.e., when the target is already visible through the live camera image).

Registration errors

Registration errors such as fixed error offset, latency or jitter, are key issues for AR set-up. Indeed such errors impair the spatial relation between the physical world or its representation on screen and the augmented content (Figure 1-D). Further, such a spatial relation is the core property of AR. As such, registration errors has been studied and experimentally evaluated. In the first survey of AR, Azuma [1] already discussed registration errors in terms of static and dynamic errors. Holloway [5] proposed a model to analyze registration errors of an optical see-through head-mounted display used for surgery planning.

Experimental evaluations on registration errors follow two strategies. On the one hand, some experimental protocols use an immersive Virtual Reality (VR) set-up to simulate an AR set-up. This allows a precise control of the different parameters of the simulated AR set-up that would otherwise be impossible. Ventura et al. [15] experimented with the effects of different field-of-views and duration of registration dropouts while performing a target following task with X-ray vision. They found a significant effect of both field-of-view and dropout's duration. With such a setting, Ragan et al. [10] evaluated the effect of latency and jitter while performing a ring-guiding task along a crooked path. They observed effects of both latency and jitter. Their results suggested that jitter was the dominant type of error. Lee et al. [6] also found an effect of latency on a ring-guiding task. They also studied the effect of the latency of the VR environment and found that it has a significant effect on the performance of the task. So, simulating AR set-up in a VR environment might have a significant effect on the results.

On the other hand, some experiments used an AR set-up and introduced artificial registration errors. Livingston and Ai [7] held an outdoor experiment with a target following task with X-ray vision. They found that high latency impaired performance and that static orientation error and registration jitter effects were not as important as expected. Yet, users believed that registration jitter was the most detrimental. Robertson and MacIntyre [11] evaluated the effect of digital graphic context as a mean to overcome registration errors while placing a brick at the position indicated by the augmentation. They found graphic context to be useful. Coffin et al. [4] evaluated the impact of recovery density on registration recovery time for key frame-based and model-based tracking mechanisms. As opposed to the other studies presented here, this study was held with a handheld tablet device.

We also based our experimental study on a handheld AR set-up by considering a smartphone and a tablet. We chose to evaluate the effect of registration jitter as in [10] and [7] since we expected this type of registration error to be detrimental to pointing adjustment accuracy and to user's visual perception.

Filtering

The effect of jittery inputs on interaction can be mitigated by filtering such inputs. Yet, filtering implies a trade-off between jitter and lag, both having an impact on interaction. Filtering can be applied directly on the jittery input signal as for example the One Euro filter [3]. This filter uses an adaptative cut-off frequency to reduce lag at high speed while stabilizing the input signal at low speed. Filtering can also be implemented as part of the interaction technique. For example, for laser pointer interaction, Olsen et al. [8] proposed widgets that react after laser dwell. This solution copes with both hand tremor and laser point tracking errors but reduces the interaction speed. Similarly for ray-casting pointing with AR head-mounted display, Olwal et al. [9] used statistical indicators about objects' positions within the selection volume across a time window.

It is possible to enhance both *Crosshair* and *Relative Pointing* by filtering the camera position returned by the tracking system system. Yet, having a pointing technique robust against jitter is beneficial as it minimizes the need for filtering and thus reduces interaction lag that is inevitably induced by filtering.

EXPERIMENT

We held an experiment on both handheld tablet and one-handed handheld device (i.e., phone) form factors. In this experiment, we compared the following two handheld AR pointing techniques in two conditions of registration jitter:

- *Crosshair*: A screen-centered crosshair indicates the pointing position. Validation is triggered on finger lift with a tap anywhere on the screen.

- *Relative Pointing*: The cursor is bound to the augmented scene attached to the physical image. The cursor is initially placed at the center of the physical image. Finger strokes control the cursor displacement with a 1:1 control-to-display (CD) ratio on the screen. Finger lift triggers the validation, thus neither finger clutching nor cancellation are not possible.

For both *Crosshair* and *Relative Pointing*, the cursor is a red square cross with filled triangles at each end (7.7mm wide on tablet; 6.2mm wide on phone).

In this experiment we studied pointing at digital targets attached to a physical image placed on a wall. We formulated the following hypotheses:

- H1: Registration jitter impairs the accuracy of *Crosshair*. The cursor is fixed on the screen where the targets are not stable.

- H2: Registration jitter does not impair the accuracy of *Relative Pointing*. The cursor is dependent on the same registration jitter as the targets. So, even if the cursor is not stable on the screen, it is stable relative to the targets. Yet, registration jitter might be detrimental to visual perception and so it might still impair pointing accuracy.

- H3: Overall *Relative Pointing* is more accurate than *Crosshair*. The stabilization provided by *Relative Pointing* also copes with natural hand tremor [16].

Relative Pointing used in this experiment differs from the one described in [16]. In [16], we evaluated *Relative Pointing* as an interaction technique. In this experiment we focus on the indirect relative pointing mode only, when finger touch input controls the cursor displacement in a relative manner. So, for this experiment we simplified *Relative Pointing* proposed in [16] to its core: Participants cannot choose between absolute and relative pointing mode and only the relative pointing mode was available. As such it is not meant to be a complete interaction technique in contrast to [16].

We also used a 1:1 CD ratio as it is a baseline that a well designed dynamic transfer function should beat. A 1:1 CD ratio was sufficient to perform the pointing tasks of this experiment in a single finger stroke on the screen. Also, as *Relative Pointing* is meant to perform pointing adjustment, movements should be of limited amplitude.

Finally, we chose to trigger the validation on finger lift to simplify *Relative Pointing*. While this limits cursor displacement, it was sufficient to perform this experiment. Whether triggering the validation on finger lift or with a tap on the screen (as in [16]) is a trade-off between faster interaction (as no tap is required to validate the selection) and richer interaction (finger clutching, cancellation, preview of the pointed position before validation).

Procedure and Design

This experiment was carried out applying the cyclical multi-direction pointing task paradigm of ISO9241-9 [14], adapted to a handheld AR set-up (see Figure 2). An image was placed vertically on the wall at 1.5m from the ground. This image had no meaningful content as the pointing task was performed outside any useful context. It only provides a background area to overlay the digital targets with good features for the vision-based tracking system we used. On the screen of the handheld device, 13 digital targets arranged in a circle were overlaid on this physical image. Targets to acquire were highlighted in blue and always in the same following order: starting from the top target, the next target was always opposite and slightly clockwise to the selected one. In case of a failed acquisition, the target turned dark red; otherwise it

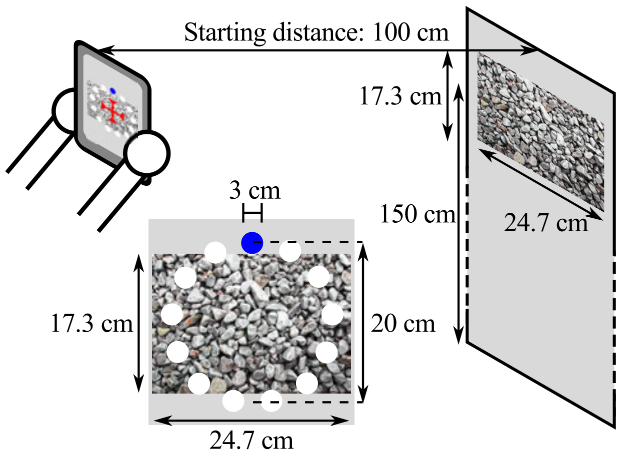

Figure 2. Experimental set-up.

reverted to white. The goal was to provide an immediate feedback of success or error to the participants.

Participants performed the task while standing-up in front of the physical image. Before each block, participants had to place the handheld device 1 meter $\pm$ 5cm away from the physical image by following indications displayed on the screen. Those indications were hidden as soon as participants acquired the first target. With the handheld tablet, participants were instructed to hold the device in portrait mode with both hands and to interact with their thumbs. With the phone, participants were instructed to hold the device in portrait mode with their dominant hand and to interact only with this hand.

We tested two conditions of registration jitter: (1) That of the underlying tracking system as is and; (2) Extra artificial translational noise added to the relative position of the physical image (with a pseudo-normal distribution of mean 0 and 5mm standard deviation). This is consistent with Ragan et al. [10] who varied the translational jitter standard deviation between 0 and 11.43mm.

We used one movement distance D (20 cm on the physical image) and one target Width W (3cm on the physical image). The Index of Difficulty of this task is $log2(D/W + 1) = 2.9$ bits. From 1 meter $\pm$ 5cm, on the screen of the phone D is within [1.7-1.9] cm and W is within [0.25-0.3] cm. On the screen of the tablet, D is within [4.6-5.2] cm and W is within [0.7-0.8] cm. With such D and W on the screen and a 1:1 CD gain for *Relative Pointing*, it is possible to reach the targets with a single thumb stroke on both devices. With this set-up, the physical image on the wall remains in the field of view of the camera at all times while performing the task.

We used a mixed experimental design with repeated measures. *Device* was a between-subjects independent variable. Half of the participants performed the experiment with a handheld tablet and the other half with a smartphone size handheld device. *Technique* and *Registration jitter* were within-subject independent variables. The presentation orders of both *Technique* and *Registration jitter* were counter-balanced across participants using a Latin square. The within-subject experimental design was:

2 Techniques x 2 Registration jitter x 2 Blocks x 12 Targets = 96 acquisitions per subject.

For each *Technique*, participants first performed two training blocks (one for each *Registration jitter* condition), resulting in 48 extra training acquisitions.

Apparatus and Participants

We used iPad2 (weight: 601g, screen resolution: 1024x768 - 132 dpi) for the *tablet* condition, and iPod4 (weight: 88g, screen resolution: 960x640 - 326 dpi) for the *phone* condition. Each device provides touch input with the same resolution as its screen. We developed an ad hoc application for the experiment using OpenGL|ES 1.1[1] rendering back-end and Vuforia SDK 1.5.9[2] for image tracking. This application runs at about 30 frames/s on iPad2 and 26 frames/s on iPod4. Images retrieved from the camera have a resolution of 480x640 pixels and are displayed full-screen (cropped on iPod4). Statistical analysis was performed with the R software.

Twenty-four unpaid right-handed undergraduate students in Computer Science participated in the experiment. Twelve participants (one female; age: [21-29] years, mean 23 years) performed the experiment with a handheld *tablet*. Ten used a touch-based handheld device on a daily basis and two had never used one, five had used a handheld tablet before and one had used an AR application before. Twelve other participants (three females, age: [21-27] years, mean 23 years) performed the experiment with a *phone*. All had previous experience with touch-based handheld devices (eleven on a daily basis), eight had used a handheld tablet before and four had used an AR application previously.

Statistical Results

We checked the distance between the physical image and the handheld device at which target acquisitions were performed. Overall average distance from the physical image is 99.5cm (1st quartile: 97cm, 3rd quartile: 102cm, range: [89cm-113cm]). This indicated that the constraint to place the handheld device 1 meter $\pm$ 5cm away from the physical image before starting a block succeeded in confining the distance between the handheld device and the physical image to a small range.

We explored the effects of the *Technique*, *Registration jitter* and *Device* factors by analyzing two dependent variables: *Errors* and *Duration*. Figure 3 depicts the dependent variables separately on both *Devices* for each *Technique* and *Registration jitter*. Table 1 sums up the values of the dependent variables for each condition. We recorded 2304 target acquistions. We kept all observations during the following analysis.

Errors

Table 2 sums up error rate for each factor. We tested the dependence between errors and the different factors with Pearson's Chi-squared test with Yates' continuity correction. We did not found a significant dependence of errors on *Blocks* (χ^2 = 0.504, p=.48).

[1] http://www.khronos.org/opengles/1_X/
[2] https://www.vuforia.com/

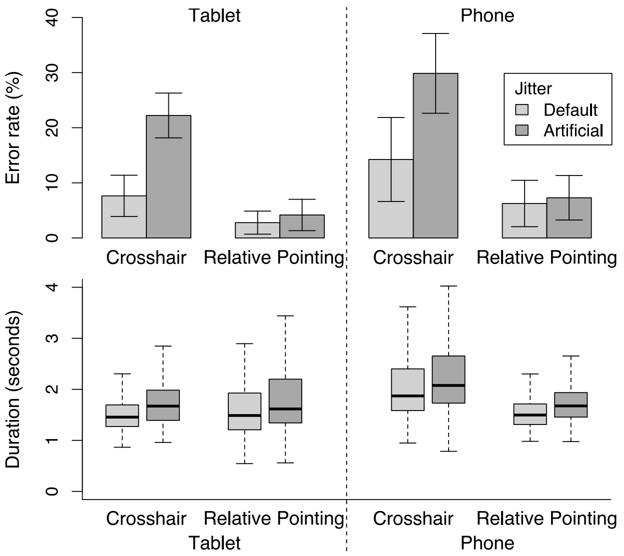

Figure 3. (Top) Barplots of error rates (%) with 95% CI of error rates aggregated by participant; and (Bottom) boxplots of target acquisition durations (seconds) for each *Technique* and each *Registration jitter* for each *Device*.

Over all the observations, significant dependences were found for *Technique* (χ^2 = 97.583* [3]), *Registration jitter* (χ^2 = 36.054*) and *Device* (χ^2 = 14.511, $p<.001$). We further analyzed the dependence between errors and *Registration jitter* for each *Technique* on each *Device*. For *Crosshair*, Pearson's Chi-squared test found a significant dependence between errors and *Registration jitter* on both *Devices* (tablet: χ^2 = 22.977*, ϕ = 0.20; phone: χ^2 = 19.556*, ϕ = 0.18). For *Relative Pointing*, no significant dependence was found (tablet: χ^2 = 0.466, p=.49, ϕ = 0.03; phone: χ^2 = 0.11, p=.74, ϕ = 0.01). Post hoc power analysis indicated a power of 0.67 for small effect size (0.1) and a power of 0.99 for medium effect size (0.3).

Duration

Table 2 sums up mean duration and standard deviation for each factor. A paired t-test found a significant mean of the differences between *Blocks* (t_{1151} = 7.559*) with the second block faster than the first one (95% confidence interval (CI): [0.09-0.16] seconds). As opposed to the error rate, this indicates a learning effect.

[3]* indicates p<.0001.

Table 1. Error rates, duration (mean ± standard deviation).

Technique	Jitter	Error rate (%)	Duration (s)
Tablet			
Crosshair	Default	8	1.51 ± 0.39
Crosshair	Artif.	22	1.71 ± 0.48
Relative Pt.	Default	3	1.62 ± 0.57
Relative Pt.	Artif.	4	1.87 ± 0.73
Phone			
Crosshair	Default	14	2.11 ± 0.79
Crosshair	Artif.	30	2.25 ± 0.81
Relative Pt.	Default	6	1.55 ± 0.42
Relative Pt.	Artif.	7	1.75 ± 0.44

We performed a 2 x 2 x 2 (*Technique* x *Registration jitter* x *Device*) mixed-design analysis of variance on median duration of aggregated repetitions with participant as a fixed factor. We found a significant effect for *Technique*, though with $p<.05$ ($F_{1,22}$ = 5.894), and *Registration jitter* ($F_{1,22}$ = 33.266*). The *Technique* x *Device* interaction was also found significant ($F_{1,22}$ = 12.340; $p<.01$). The *Device* main effect and other interactions were not found significant.

For *Technique*, a paired t-test found a mean of the differences of 0.21 seconds (95% CI: [0.05-0.37] s; t_{47} = 2.749; $p<.01$). For *Registration jitter*, a paired t-test found a mean of the differences of 0.16s (95% CI: [0.11-0.22] s; t_{47} = 5.876*). To further study the interaction *Technique* x *Device*, we ran paired t-tests separately for both *Devices*. For *tablet*, the paired t-test was not significant (t_{23} = 1.223; p=.23). For *phone*, we found a mean of the differences of 0.53s (95% CI: [0.31-0.73] s; t_{23} = 5.155*) with *Crosshair* being slower than *Relative Pointing*.

DISCUSSION

For this experiment, *Registration jitter* impaired the accuracy of *Crosshair* as indicated by its significantly higher error rate with artificial jitter. This experiment did not show a significant effect of *Registration jitter* on *Relative Pointing* error rate. Yet, for both techniques, the target acquisition duration increased with artificial jitter. This supports the hypothesis H1 and partly supports the hypothesis H2. Indeed, the accuracy of *Relative Pointing* was not significantly impaired by *Registration jitter* as was the case for *Crosshair*. Yet this does not imply that *Registration jitter* has no effect on *Relative Pointing* accuracy. Furthermore, *Relative Pointing* performance was impaired as target acquisition duration increased under the artificial jitter condition.

The error rate of *Relative Pointing* was smaller than that of *Crosshair*. Also, *Relative Pointing* was overall faster than *Crosshair*. This supports the hypothesis H3.

On the one hand, for *Crosshair*, both error rate and acquisition duration varied across the different conditions. Our hypotheses can explain such variations, but other effects might also interfere. Indeed *Crosshair* had a rather high error rate across all conditions. This can indicate that *Crosshair* operated here close to its limit of precision. If we interpret the effect of the artificial jitter as a reduction of the target width, and if *Crosshair* was used at its limit of accuracy, then part of the increase of the error rate might be due to the limit of precision. *Crosshair* performed worse on *phone* than on *tablet*. This might be related to

Table 2. Error rates, duration (mean ± standard deviation) for each factor.

Factor	Error rate (%)	Duration (s)
Overall	12	1.80 ± 0.65
Crosshair	18	1.90 ± 0.71
Relative Pt.	5	1.70 ± 0.57
Default Jitter	8	1.70 ± 0.61
Artif. Jitter	16	1.90 ± 0.67
Tablet	9	1.68 ± 0.57
Phone	14	1.90 ± 0.70

the tracking failures mainly observed with *Crosshair* on *phone* and to the lower processing power of the *phone* we used. This might also be due to the difference of hold of the device (one-handed vs. two-handed). Yet, with our experiment we cannot conclude on this point.

On the other hand, for *Relative Pointing*, results suggest that both error rates and acquisition durations varied less across *Registration jitter* and *Device* conditions. As explained in hypothesis H2 the cursor is stable in the frame of reference of the targets. This can explain the stability across *Registration jitter* conditions. The low variation across *Devices* can be explained by the fact that the difference between devices can be interpreted as a change of scale of the touch pointing task in motor space. Indeed, the differences between the devices in terms of camera and screen size result in different scales of both movement distance and target width on the screen. This results in pointing tasks in motor space with different scales but a similar form (i.e., similar Index of Difficulty).

CONCLUSION

We have presented an experiment comparing the impact of both registration jitter and device form factor on two cursor-based pointing techniques for handheld Augmented Reality (AR): (1) screen-centered *Crosshair*; and (2) *Relative Pointing* in the frame of the physical object. Our evaluation indicates that the latter is less error prone than the former. Also, the accuracy of *Relative Pointing* seems less sensitive to registration jitter and to device form factor than that of *Crosshair*. We see *Relative Pointing* as a valuable candidate for pointing in handheld AR when accuracy matters.

Following this experimental study we plan to evaluate the effect of registration jitter on pointing at physical targets rather than digital ones attached to a physical image. For that case, the cursor of *Relative Pointing* would no longer be stable relative to the targets. Yet, the user might be able to compensate the registration jitter as s/he can observe this jitter through the displacement of the cursor. Future work on *Relative Pointing* also includes extending this technique to non-planar physical objects. This raises new issues to be studied such as cursor occlusion by the physical object.

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