Pointing at Physical Targets Around the Field of View of Optical See-Through Head-Mounted Displays

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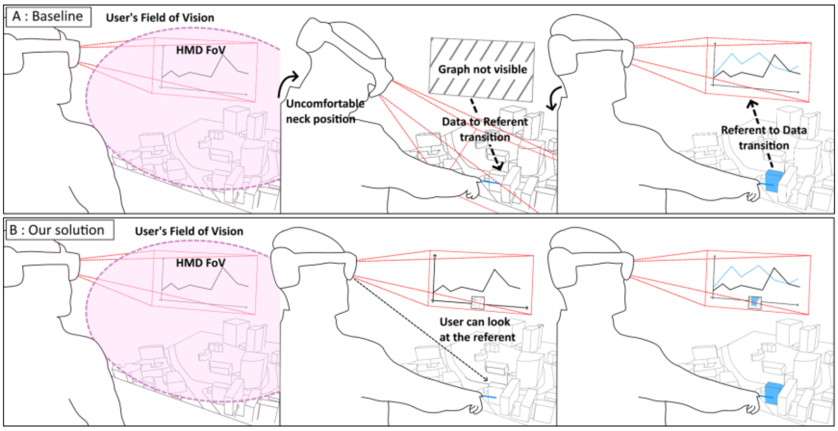

Fig. 1. Our approach is illustrated in the context of an augmented urban physical model. A building (physical referent) located in the user's field of vision (pink area) but outside the HMD FoV (red rectangle) is selected to display the associated data. A) With the regular interaction, the user needs to move the head toward the referent to display the pointing ray. This causes neck discomfort and deviates attention from the data visualization. B) Our solution lets the user directly select the physical building thanks to a Focus View displayed within the HMD FoV, showing the ray's impact point. The data visualization is still visible while the user selects surrounding physical objects, thus limiting head movements. The dotted blue ray is not visible to the user but was just added for clarity reasons in this illustration.

Abstract. With the increased availability of sensor-based data, data analysis lies at the heart of various needs, such as energy monitoring, and augmented maintenance. Presenting digital data in the context of their physical referents is now feasible thanks to AR Optical See-Through Head-Mounted displays (HMDs). However, although the display space with such HMDs is almost unlimited, their field of view (FoV) is still small: as a result, the surrounding physical referents are often positioned around the HMD FoV and cannot always be pointed at or interacted with to trigger the data display. Therefore, we designed and evaluated a set of techniques to point at objects in the User's Field of Vision but out of the HMD FoV, thus limiting head movements. Our techniques are all based on showing, at the bottom of the HMD FoV, a focus view presenting the area centered on the ray's impact point. We experimentally compared our techniques to moving the head and pointing at the target within the HMD FoV, for targets distributed on a horizontal or vertical surface. Our study shows that users perform better with our techniques when pointing at targets on a horizontal surface and perform similarly than the baseline technique on a vertical surface. We analyze the results and envision perspectives for around-FOV pointing.

Keywords: Physical target, raycasting, finger pointing, augmented reality, head-worn display.

1 Introduction

With the increased availability of sensor-based data, data analysis lies at the heart of various scenarios, such as energy monitoring [18], warehouse logistics [44], or interaction with connected objects in a smart home environment [11]. A recent trend in data visualization is called Situated Visualization: "*Visualizations displayed on phones, tablets, or laptops can become situated simply by placing the device in a relevant space or near a relevant object*" [52]. Doing so allows the user to visualize the data in the local context of a physical object that generates or is related to that data: this object is the physical referent [52], i.e. a room, a sensor, etc. In the previously mentioned situations, users can access data near their referent to benefit from the immediate physical surroundings to help make sense of the data: a building's electricity consumption near the electric meter in a house, or a product's stock history near the storage shelves in the storage shed. In such contexts, the user's task is to explore or compare data from different physical referents and annotate a physical referent or its data. As a result, these tasks require users to interact with both physical and digital objects distributed around them [7].

Augmented Reality (AR) with Optical See-Through Head-Mounted displays (HMDs) is particularly relevant for interacting with Situated Visualization: HMDs allow to display digital data close to their real-world physical referent, as illustrated in Fig. 1-Left. Besides, HMDs enable spatial exploration of data [29], offer several input modalities and provide multiple perspectives [37]. Although the size of the Optical See-Through HMDs field of view (FoV) is limited compared to Video See-Through HMDs [37, 41], they offer the advantage of enabling direct visual contact with the physical environment. However, given the limited HMD FoV, the physical referents visible within the user's field of vision may be spread around the HMD FoV, making it difficult to select them. In this context, our goal is to design interaction techniques that can be used to efficiently point at these surrounding physical targets in AR, and avoid uncomfortable and frequent head movements between the referents and the related data displayed in context. Our work contributes to improving *Interaction with situated data visualization in AR*, one of the interaction challenges of immersive analytics [17].

The literature offers a wide range of target-pointing techniques, whether physical or digital, in AR environments. Except in situations where targets are physically reachable [13, 54], two categories emerge for distant pointing: they derive either from raycasting [13, 19] or "virtual hand" [39, 43] techniques. Users generally prefer raycasting, perceived as faster and easier to use [9, 51]. Therefore, ray pointing at physical referents located outside the HMD FoV requires moving the head to place them inside the HMD FoV to see the ray's feedback (see Fig. 1-A). These head movements represent "data to referent" transitions, which are tedious, lead to an uncomfortable neck position [37], divert the user's attention from the data visualization and hinder interaction [1]. In addition, users prefer looking at physical targets around the HMD FoV rather than moving their heads toward the target [37]. An alternative could rely on techniques for labeling out-of-view objects [28]: however, given the potentially large amount of physical referents in the surroundings, such an approach would result in a high-density set of labels to display in the HMD. We, therefore, did not further consider this type of technique. Another alternative would be to always display the data in a fixed position within the HMD FoV, hence removing the "data-to-referent" transitions. However, we believe that this could result in occluding physical objects with data windows or in displaying these windows at inappropriate positions (e.g., over someone or a brightly illuminated space).

In summary, our work aims to solve the problem of pointing in AR at physical objects located around the HMD FoV without head movements. It will allow users to select physical referents spread around them to access the related data in context while avoiding cumbersome head movements, as illustrated in Fig. 1-B. More precisely, our work explores how to point at physical targets around the HMD FoV while the user visualizes data in front of him within the FoV. We focus on targets located outside the HMD FoV but inside the user's field of vision (see Fig. 1). To our knowledge, pointing at physical targets around the HMD FoV has not been studied so far.

We design and evaluate two techniques for pointing at physical targets located around the HMD FoV but in the user's peripheral vision. Our techniques are based on showing, at the bottom of the HMD FoV, a focused view reproducing an area centered on the ray's impact point (see Fig. 1-B). They differ in the ray's origin and orientation. The main result of our study is that our techniques outperform the baseline (moving the HMD FoV over the desired target) in terms of completion time, error rate and user satisfaction when pointing at physical targets distributed on a horizontal surface. However, no significant difference could be observed on a vertical surface. We further discuss these results and open new perspectives for around-FoV pointing.

To sum up, our contributions are as follows: 1) the design of techniques for pointing around the HMD FoV; 2) the comparative evaluation of our techniques against a baseline; 3) the discussion of perspectives and future works.

2 Related Work

We review previous work in pointing and selection in AR, with a particular focus on pointing at physical objects in AR.

2.1 Pointing in AR

Among the multitude of interaction solutions for distant pointing in AR [32, 39], two main categories emerge: techniques based on the "virtual hand" [39] and those based on raycasting [20].

On one hand, virtual hands have been found to be slower than raycasting for pointing at distant objects [9]. On the other hand, raycasting techniques raise an ambiguity when the ray intersects several objects. Different disambiguation solutions have been explored, including scattering the objects intersected by the ray [20], or offering a two-stage pointing, as with DepthRay and LockRay [20]. Such methods add a cursor to the ray, whose position on the ray is controlled by the user's hand, user's gaze [14, 30], or by devices such as a smartphone [40] or a controller, as with RayCursor [5]. Such solutions provide the user with an extra degree of freedom in the selection task.

Beyond disambiguation, works on raycasting pointing technique focused on the origin and orientation of the ray. Argelaguet and Andujar [3] compared hand-rooted ray, which consists of aligning the ray with the user's arm (as implemented by default in the HoloLens 2), and head-rooted ray, whose origin is based on the position of the head in a virtual environment. This work established that the head-rooted ray improves the pointing performance, allowing the user to better anticipate the point of impact. This result was also confirmed by Mayer et al. [31] who even extended its validity to real environments, as previously established by Taylor and McCloskey [47]. A last approach could consist of using a gaze-based ray, as with GazeRayCursor [14] which uses the intersection of the gaze and controller rays to disambiguate selection, and Gaze&Finger [28] which allows users to interact with content by aligning their finger with the user’s gaze. However, this origin and orientation of the ray would lead to eye movements out of the acceptable range of vision zone [1]. Additionally, in the case of wearing an AR HMD, the user would be looking outside the HMD FoV, which would prevent providing the user with any visual feedback.

In summary, these two categories of pointing techniques in AR, virtual hand and raycasting, have distinct advantages and disadvantages. The former focuses on the manipulation of distant objects, while the latter is widely preferred by users for selection and pointing tasks. Finally, multiple modalities have been considered to control these two main types of techniques: finger-[53], hand-[13], head-[16], arm-[34], gaze-[30], eye-tracking-[30] or controller-based [20].

2.2 Pointing at physical objects in AR

In the literature, few studies focus on pointing at physical objects using raycasting [13, 19, 54]. For instance, to interact with fragile historical objects in museums, TouchGlass [13] examined pointing at a distance through a glass using a raycasting technique perpendicular to the glass. The work of Freeman et al. [19] explored the object vibration as a feedback for pointing at small levitating objects. In the context of urban mobility, Shift&Freeze [49] is a technique, inspired by Overview+Details interfaces [42], enabling the user to select a precise location on a physical wall map in two steps process using a smartphone: a first tap freezes the display and a second selects a precise location on the smartphone, greatly limiting the effect of the instability of the smartphone.

In summary, most of these techniques focus on pointing at physical objects in the HMD FoV. However, the major limitation of HMDs is their reduced FoV, much smaller than that of the human eye: the user can perceive a larger part of the physical space than the HMD can enrich by displaying digital data. Taking advantage of the user's larger field of vision requires to consider pointing at physical objects located outside the HMD FoV but within the user's field of vision.

2.3 Locating objects out of AR devices' FoV

Previous research has developed various visualization techniques to address the challenge of locating targets beyond the AR devices' FoV, whether on smartphones or HMDs. The radius of a circle may encode the distance to the target as in Halo [6, 35]; the basis of isosceles triangles may better express the direction of the target than the circle, as in Wedge [24]; a miniature representation of the targets can be displayed on the screen edge, as in EdgeRadar [25], or directly on the screen, as with EyeSee360 [22]; simply displaying arrows was also studied in Scaled-Arrow and Stretched-Arrow [12]. A comparative study against EdgeRadar and Halo in AR favoured the 3D version of Halo, called Halo3D [36]. Wecker et al. [50] also evaluated different forms of guidance, only for one target at a time, and without supporting the perception of all existing targets around the HMD FoV. To help reason about these solutions, Assor et al.'s [4] outlined a design space for visualizing physical referents out of the user's FoV. Finally, beyond representations, activating LEDs placed on the HMD in the user's peripheral vision [23] has also been considered. However, these works focus on locating or visualizing objects surrounding the AR device FoV but do not encompass interaction with such objects.

2.4 Conclusion

Numerous pointing solutions in AR have been proposed, with a preference for object pointing based on a raycasting technique [9, 20]. For these raycasting techniques, it has been established that a head-rooted ray improves the pointing performance, allowing the user to better anticipate the point of impact [2]. Recent works have focused on pointing at physical objects in AR [13, 19], and not just digital entities. A significant limitation of HMDs is, however, their small FoV which can hinder users to access objects located outside of it. Although guiding the user to these targets has been explored [21, 35], the user is still constrained to move the head and look at the target. In contrast, driven by the benefits of Overview+Details interfaces in AR [49], the novelty of our work is to explore pointing at physical objects located around the HMD FoV (i.e. outside the HMD FoV but inside the human field of vision) without moving the head.

3 Design of Around-FoV Pointing Techniques

In this paper, we propose two around-FoV interaction techniques to facilitate pointing at physical objects around the HMD FoV. We first present two usage scenarios based on ongoing projects, the considered design factors and the techniques themselves.

3.1 Usage scenarios

We explore two usage scenarios from the literature on situated analytics, one focusing on urban situated analytics [7, 38], and the other on situated logistics management [52].

Augmented Physical Model for data analysis. Urban planners brainstorm about the urban management of a district using 3D models provided by architects. The main buildings and points of interest (such as metro or bus stations) are represented by fixed physical cubes. This model is enriched with numerical data of the urban mobility. Urban mobility is of major importance and so Alice, an urban planner, wears her AR HMD to study the flow of students entering and leaving a university building in relation to public transport stations located around it. While analysing the data graphs displayed above the campus model, Alice can filter the data by selecting nearby physical objects such as metro or bus stations, even if they are outside the HMD FoV.

Logistic management. Daniel, a logistics operator responsible for stock management in a warehouse, uses an AR HMD to monitor stock levels. While walking through the storage facility, designating a place on a shelf allows him to examine the full stock history of the product exposed on this shelf without having to move his head up and down frequently. By selecting the product, he gets a detailed overview of its stock history, enabling him to make informed decisions about replenishment requirements.

3.2 Design Factors

Pointing with reduced visual feedback leads to progressive deviations from the intended target [15]. To solve this problem while supporting the raycasting-based selection of targets around the HMD FoV, we propose to dedicate a small space inside the HMD FoV to the feedback: the focus view. In the focus view is rendered an area centered on the ray's impact point (i.e. where it collides with a physical object or surface) around the HMD FoV, as illustrated in Fig. 2-A. To design this technique, we considered the origin of the camera displaying the ray's view, the size of the area reproduced, the size and position of the focus view and the origin and orientation of the ray.

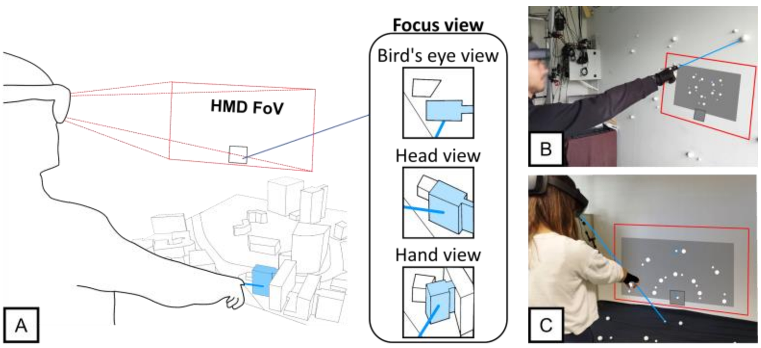

Fig. 2. Illustration of our design factors. Three virtual camera positions (Bird's eye, Head, Hand) (A); Form of the ray: hand-rooted (B) and head-rooted (C). The red rectangle is the HMD FoV and the blue line the pointing ray. They are represented on the figure for illustrative purposes but are not displayed in real use.

Virtual camera position. This factor describes the position of the virtual camera used to render the detailed view of the point of impact of the ray. Placing the camera on the user's head would be consistent with how users perceive the real physical environment. Alternatively, placing the camera perpendicular to the plane where objects are located would provide a bird's eye view with the 2D layout of the objects. Finally, the camera could be positioned on the user's hand. This would allow the user to adapt their view according to the orientation of their hand (see Fig. 2-A).

Size of the area around the ray's impact point. This factor characterizes the size of the physical area reproduced in the focus view. With a small physical area reproduced, a big representation of the physical objects will be provided. The counterpart is the difficulty in locating them in their surroundings. Conversely, with a large area, it will be easy to locate objects but difficult to select them due to their reduced size.

Size and position of the focus view on the HMD FoV. The bigger the size of the focus view, the smaller the remaining space in the HMD FoV to display other information. In addition, its position in the HMD FoV influences the ease with which the user can see this area and the occlusion of the vision through the HMD. A view placed in the center of the HMD FoV will always be visible but may occlude the content located behind it. Placing the view at one corner of the HMD FoV will reduce the occlusion but may be more difficult for the user to see [1]. Instead, placing the focus view at the bottom center seems to be a good compromise to enhance its visibility.

Form of the ray: origin and orientation. Finally, the last factor to consider is the origin and orientation of the ray. As presented in the Related Work section, in comparison to hand-rooted ray, a head-rooted ray improves the pointing performance; our hypothesis is that it will also be the case in AR.

3.3 Interaction techniques design rationale

We adopted an iterative approach to inform the design of our techniques for pointing around the HMD's FOV: we produced a series of prototypes and conducted informal tests to choose the most appropriate value for the previously introduced design factors.

Regarding the **virtual camera position**, we adopted a position on the "head" of the user: the bird's eye view induced a strong mismatch with the direct view of the target by the user in his peripheral vision, and placing the camera on the "hand" was not comfortable for the user, due to the continuous camera movements [27].

Regarding the **size of the area** around the ray's impact point, we empirically adopted a 20x20cm surface: it allows the targets to be pointed at satisfactorily while ensuring good visibility of both the targets and their surrounding environment.

For the focus view design, we empirically set the **width of the focus view** to be 1/8 of the width of the FoV. We set the **position of the focus view** at the bottom center of the HMD FoV: this placement makes it easier for the user to look at it while minimizing the occlusion of the AR environment.

Finally, concerning the **form of the ray**, we kept the two **forms of the ray** discussed above: hand-rooted ray and head-rooted ray, which we respectively named Arm (see

Fig. 2-B) and Head-To-Finger (see Fig. 2-C). Before using the Head-To-Finger technique, the user defines the point of origin on his forehead above his nose with his finger.

We, therefore, implemented two techniques that permanently display, in the HMD FoV, a focus view rendering an area around the ray point of impact.

4 User Study: Around-FoV Pointing

In this study, we compare the two interaction techniques introduced in the previous section to point at targets around the HMD FoV (Arm and Head-To-Finger) with a baseline from our literature review [20], the Direct Pointing technique. First, we briefly remind the principles of the Arm and Head-To-Finger techniques and introduce the baseline technique. Then, we detail the position of the targets, the experimental task and protocol, the participants and the setup. Before presenting the results, we describe how we collected and analyzed data.

4.1 Studied Techniques

In this study, we compare the two techniques presented in section 3 (Arm and Head-To-Finger) with the Direct Pointing technique.

The **Arm** and **Head-To-Finger** techniques provide the user with a focus view of the impact point. A virtual camera is placed on the "head" of the user (see Fig. 2-A) and captures an area of 20x20cm around the ray's impact point. This capture is rendered in the focus view. The Focus view width is an 1/8 of the width of the HMD FoV and is placed at the bottom center of the HMD-FoV. A hand-rooted ray is used for the Arm techniques and a head-rooted ray is used for the Head-To-Finger technique.

The **Direct Pointing technique** (illustrated in Fig. 1-A) is the sole and traditional raycasting technique commonly used in existing HMDs and represents a straightforward approach for accurate object pointing outside the HMD FoV. With this technique, the ray takes its origin in the user's hand, and its direction follows the arm direction. However, to see the ray feedback, the target must be visible in the HMD FoV, thus forcing the user to move their head to place the target inside the FoV. In this way, we can compare pointing without and with head movements (Fig. 1).

4.2 Position of the targets

Fig. 3. Targets distribution on the horizontal (left) and vertical (right) surfaces (schematic and real).

Targets were physical spheres positioned on a surface. To reflect the different conditions illustrated in the use cases (section 3.1), we decided to test two target sizes (2cm and 4cm). In addition, our usage scenarios show that physical referents can be spread over a horizontal surface (augmented physical urban model for data analysis scenario) or vertical surface (logistics management scenario). Hence, we included both surfaces in our experimental protocol. In both cases, targets of both sizes were fixed and the arrangement of objects followed a pattern where the objects of both sizes were paired while maintaining a 10° spacing between the two targets of each pair. To explore the impact of target distance, targets were spread on two circles of different sizes (0.5m and 1m): the HoloLens 2 FoV is inscribed within a circle with a radius of 0.39m for a user positioned 1m away: hence all our targets were outside the HMD FoV. We detail the setup for each surface below.

Horizontal surface. Targets were spread over two horizontal half-circles positioned in front of the users (Fig. 3-left). Users were standing on a step to keep a distance of 1m between the surface and the users' shoulders. Users were positioned in front of the half circles and at a distance of 1m above and 30cm in front of the center of the circles.

Vertical surface. Targets were spread over two vertical circles (Fig. 3-right). On the smallest circle, targets are uniformly distributed in pairs every 72°. However, the upper part of this distribution cannot be used on the largest circle because of the physical occlusion due to the HMD headband: therefore, we lowered these two pairs to ensure their visibility by the user. For the tasks performed with this surface, users were facing the center of the circle at a distance of 1m. from the vertical surface.

4.3 Task

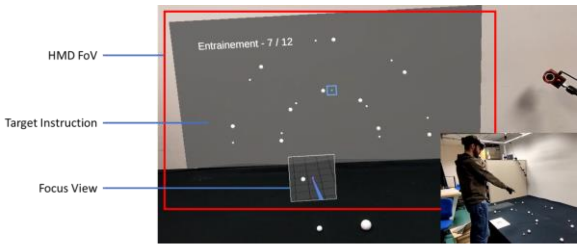

Fig. 4. View (HoloLens 2 and external) of a user pointing at a target on the horizontal surface: the red rectangle depicts the HMD FoV but is not visible by the user

The instruction was to point as quickly and accurately as possible at each physical target with the dominant hand. To begin a trial, the user's hand had to be brought back alongside the body to ensure a consistent user's initial position. As described in Fig. 4, an instruction representing the position of all the physical objects was displayed in the center of the HMD FoV, with the trial's target highlighted. To reflect the scenario that minimizes frequent head motions between referents and data, participants were requested to keep the head oriented straight ahead when using Arm and Head-To-Finger techniques. Still, participants could look at all physical targets without moving their heads since all targets were within the human field of vision. The target was also highlighted as soon as it appeared in the Focus View. In contrast, it was impossible to keep looking ahead when using the Direct Pointing technique: to avoid any risk of omitting which target to select, the physical target was also highlighted, once visible in the HMD FoV. Once the user was pointing at the target, participants had to press a button held in their non-dominant hand to validate the pointing and end the trial. The trial could not end before the target was correctly selected.

4.4 Experimental Protocol

The study followed a 2x3x2x2 within-subjects design, with the following factors: the surface (horizontal and vertical), the pointing technique (Direct Pointing, Arm and Head-To-Finger), the distance of the targets from the center of the surface (0.5m and 1m) and the target size (2cm and 4cm). The study consisted of six blocks, each corresponding to the combination of one surface and one pointing technique. During the experiment, the order of the block is counterbalanced across participants. Hence, the order of techniques over participants is controlled. The order of the targets followed an increasing difficulty: participants had to select the closest targets (i.e. at 0.5m from the center of the surface) first and then the furthest (1m); for each distance, users had to point at the biggest targets before the smallest ones. During a block, the participant points twice at each target of a given size and distance in a random order. In this way, a block consists of pointing at 40 targets on a given surface (2 repetitions x 2 sizes x 2 distances). At the beginning of each block, participants carried a training session consisting of pointing at three random targets among the possible targets for each combination of distance and size. The whole experiment lasted around 60 min.

4.5 Participants

We recruited 12 right-handed volunteers (seven self-reported as male and five self-reported as female) ranging from 19 to 27 years (mean=23.33, SD=2.8), with an AR experience self-evaluated at 2 on a five-point Likert scale revealing that our participants are non-AR experts. A score of 1 indicated no experience or knowledge of AR, while a score of 5 represents a participant who regularly uses an AR HMD in daily life. All were working in the computer science field. Our study has been declared to the local ethics committee and complied with their procedures.

4.6 Setup

We developed a Unity application written in C# using the MRTK 2.8 library with a HoloLens 2 connected to a laptop using Holographic Remote application. Participants were standing throughout the study. To track the user's hand precisely (with a 0.8mm error), we used the Optitrack 2.3 system: participants wore a glove equipped with six IR markers and tracked by ten Flex 3 cameras. During all the trials involving the Arm and Head-To-Finger techniques, the participants were asked not to move their heads, so that the targets were always around the HMD FoV. If the participants moved their head outside a tolerance zone (59.7° horizontal, 45° vertical) centrally aligned with the HoloLens 2 FoV (43° horizontal, 29° vertical), the HMD displayed a red sign in front of users to invite them to move their head back to the tolerance zone and the pointing task feedback was suspended. The size of the tolerance zone ensured that the targets were always outside the HMD FoV while not forcing the user to keep his head in a fixed position, which might affect comfort and performance [48].

4.7 Collected Data

For each trial, we collected the usual data of target selection evaluations [8]: completion time, number of crossing on the target, as well as the hand's height during pointing. At the end of each block, i.e. for each combination of surface and technique, participants completed the unweighted version of the NASA-TLX form [33] to assess the task workload. At the end of each surface, participants had to rank the three techniques in a preference order. On one hand, quantitative data allows to assess the overall performance of users with the different considered techniques, an important aspect when the task is repetitively performed. On the other hand, qualitative data supports the assessment of subjective aspects of the techniques that may be of particular importance in situations involving the techniques for a long period.

4.8 Data Analysis

During the study, we collected 240 trials per user (2 surfaces x 3 techniques x 2 distances x 2 sizes x 5 targets x 2 repetitions), i.e. a total of 2880 trials. We used ANOVA to analyze the results (F, p, η^2) and pairwise T-tests, except when the normality assumption was violated (Shapiro-Wilk normality test) even after using a log function. In such cases, we conducted a Friedman test ($\chi 2$, p, n), followed by a pairwise Wilcoxon test with Bonferroni correction. All confidence intervals are constructed as 95% bias-corrected and accelerated (BCa) bootstrap intervals with 10,000 replicates. Our bootstrap technique relies on a deterministic strategy. Prior to data analysis, we proceeded to replace outliers from our data using the three-sigma method, i.e. values greater than three times the standard deviation from the mean. This operation replaced 60 trials from the total dataset of 2880 trials (2%).

4.9 Results

We did not observe any effect of the order of the blocks on completion time, so we processed all the data together. In the following sections, we analyze the results of the two surfaces separately (horizontal and vertical).

Completion time.
We first analyzed the completion time of the three techniques (Direct Pointing, Arm, and Head-To-Finger) for each of the two surfaces (horizontal and vertical) and refined the analysis by considering the different combinations of size and distance. All results

are illustrated in Fig. 5 and detailed in Appendices A.1 and A.2 (Friedmann results, means, CI and Wilcoxon tests results).

Horizontal surface: we found a statistically significant difference between the techniques ($\chi2(2) = 15.17$, $p = 0.0005$). Post hoc analyses revealed that on overall Direct Pointing (5.39s [CI=5.19, 5.61]) requires significantly more time than our two techniques, Arm (4.72s [CI=4.50, 4.99]) and Head-To-Finger (4.40s [CI=4.22, 4.61). No clear difference could be established between our two techniques.

Furthermore, the results revealed statistically significant differences in completion time between the techniques for each of the four combinations of target size and distance, except for far small targets. For these three combinations, post hoc analyses confirmed that Head-To-Finger and Arm techniques are significantly more efficient than the Direct Pointing technique (see Fig. 5). In addition, in the two conditions involving near targets, results established that the Head-To-Finger technique performs better than the Arm technique.

Vertical surface: we also found a statistically significant difference between the techniques ($\chi2(2)=8$, $p=0.0183$). Post hoc analyses established that on overall Direct Pointing (5.38s [CI=5.19, 5.60]) requires significantly less time than our two techniques, Arm (7.45s [CI=6.94, 8.07]) and Eyes-To-Finger (6.47s [CI=6.10, 6.91]). No clear difference could be established between our two techniques.

However, when considering each combination of target size and distance separately, no significant difference between Direct Pointing and Head-To-Finger is established. The only significant difference that we observe is in the case of Small x Far targets: Arm is the least efficient technique compared to Direct Pointing and Head-To-Finger.

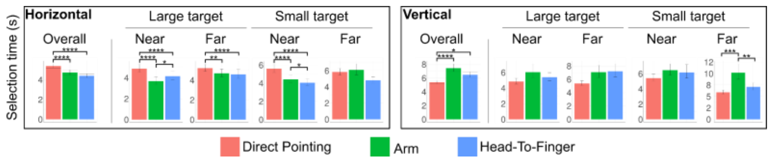

Fig. 5. Mean completion time (s) per surface and technique (left), per surface, technique, target size, and distance (right) (95% CI)

Hand's height during pointing.

The hand's height represents the difference of height between the user's hand and the user's head. It is negative unless the user's hand is raised higher than the head. We normalized the values of hand's height across participants (see Fig. 6-left). As for completion time, all results are illustrated in Fig. 6-right, synthesised below and detailed in Appendix A.3 and A.4.

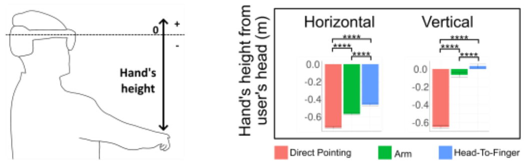

Fig. 6. Illustration of hand's height during pointing (left). Hand's height (m) per surface and technique (95% CI) (right).

Horizontal surface: There was a statistically significant difference in the hand's height across techniques ($\chi2(2) = 16$, $p < 0.0001$). Post hoc analyses established that our techniques require raising significantly more the hand than Direct Pointing ($p < 0.0001$) and, among our techniques, Head-To-Finger significantly more than Arm ($p < 0.0001$). The hand's height was -0.73m [CI=-0.73, -0.71] with Direct Pointing, -0.57m [CI=-0.58, -0.56] with Arm, and -0.46m [CI=-0.48, -0.45] with Head-To-Finger.
These results are also observed when considering the different combinations of targets' size and distance ($p<0.05$), except for Small Near targets with which no significant difference was established between Direct Pointing and Arm.

Vertical surface: There was a statistically significant difference in the hand's height across techniques ($\chi2(2) = 16$, $p < 0.0001$). Post hoc analyses established that our techniques require raising significantly more the hand than Direct Pointing ($p < 0.0001$) and, among our techniques, Head-To-Finger significantly more than Arm ($p < 0.0001$). Users had to raise their arm very high when using the Arm (-0.07m [CI=-0.09, -0.04]) and Head-To-Finger techniques (0.03m [CI=0.01, 0.06]), in contrast with the Direct Pointing technique (-0.65m [CI=-0.67, -0.64]).
These results hold with any combination of targets' size and distance.
These results can be explained because, with Head-To-Finger, the user has to raise the finger to the level of the head. In contrast, with Arm the user raises only the forearm to limit fatigue [26]. Finally, with Direct Pointing, the presence of feedback of the whole ray allowed the users to keep the hand at a lower position.

Target crossings.
Given the definition of our experimental task, all trials ended with a successful target selection. To analyze the precision of our techniques, we recorded the number of crossings for each target. The number of crossings is the number of times the ray enters or exits the target, which can reflect that a user struggles to point at it accurately. Results are summarized in Fig. 7, synthesized below and detailed in Appendix A.5 and A.6.

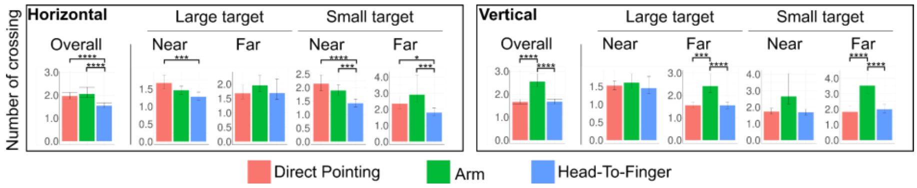

Fig. 7. Number of target crossings per surface and technique (left), per surface, technique, target size and distance (right) (95% CI)

Horizontal surface: There was a statistically significant difference in target crossings between the techniques ($\chi2(2) = 10.5$, $p = 0.005$). Post hoc analyses revealed that the Head-To-Finger technique produces significantly less crossings (1.54 [CI=1.45, 1.67) than Arm (2.05 [CI=1.90, 2.34]) and Direct Pointing (1.96 [CI=1.83, 2.11]) techniques.

A refined analysis considering each combination of target size and distance separately confirmed significant differences in target crossings between Head-To-Finger and Direct Pointing techniques except for Large x Far targets. This analysis also confirmed significant differences between Head-To-Finger and Arm techniques but only for small targets (near and far).

Vertical surface: There was a statistically significant difference in target crossings between the techniques ($\chi2(2) = 13.17$, $p = 0.001$). Post hoc analyses established that the Arm technique led to significantly more crossings (2.55 [CI=2.32, 2.88) than Direct Pointing (1.66 [CI=1.58, 1.76]) and Head-To-Finger techniques (1.67 [CI=1.57, 1.79). No clear difference could be established between Direct Pointing and Head-To-Finger techniques ($Z = 1.04$, $p = 1$).

A refined analysis considering each combination of target size and distance separately confirmed that the Arm technique produces significantly more crossings than Direct Pointing and Head-To-Finger but only for targets that are far. This analysis did not reveal any significant difference between Direct Pointing and Head-To-Finger techniques.

Ranking of techniques per surface.

At the end of all the trials on a given surface, users were asked to rank the three techniques for that surface, without distinguishing the combination of targets' size and distance. We analyzed this ranking by computing for each technique the sum of ranks obtained. Results are illustrated in Fig. 8.

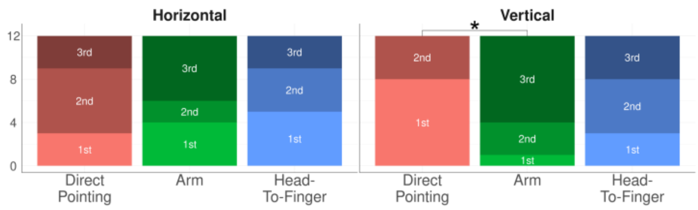

Fig. 8. Ranking of the preferred techniques per surface.

Horizontal surface: The Friedman test on ranking between the techniques did not reveal any significant difference between the techniques' ranks ($\chi2(2) = 0.67$, $p = 0.72$).

Vertical surface: There was a statistically significant difference in ranking between the techniques, $\chi2(2) = 9.5$, $p = 0.009$. Post hoc analyses established that users prefer Direct Pointing (1.33 [CI=1.08, 1.58]) over the Arm technique (2.58 [CI=2.00, 2.83]): this last technique was ranked 3rd 8 times out of 12. However, no clear difference can be established between the Direct Pointing and Head-To-Finger techniques (2.08 [CI=1.58, 2.42]) and between our two techniques.

NASA-TLX.

We conducted ANOVA and Tukey tests for each surface to assess differences in NASA-TLX subjective dimensions between techniques. No significant differences were found across the dimensions when considering the horizontal surface.

With the vertical surface, the analysis revealed a significant difference between techniques for the **effort** dimension ($F(2,33) = 3.8$, $p = 0.033$, $\eta^2 = 0.19$). However, a post hoc analysis did not establish any significant difference between Head-To-Finger (52.9 [CI=39.2, 65.8]) and Direct Pointing (32.3 [CI=23.6, 48.2]); a post hoc analysis only established that Direct Pointing induces significantly less effort than the Arm technique (54.1 [CI=36.4, 68.6]). This result confirms our previous analysis of the hand's height when pointing with Arm: in this case, the users have to raise the hand higher than with Direct Pointing. No other significant difference could be established for any of the other NASA-TLX dimensions with the Horizontal or Vertical surfaces.

5 Discussion

In this paper we introduced and studied two techniques for pointing in AR at physical targets around the HMD FoV, but in the user's FoV and without requiring head movements. Our techniques are based on the use of a focus view in which is reproduced an area centered on the ray's impact point. In this section, we review the main results of our study, discuss some limitations of our work and present some research perspectives.

5.1 Overview and analysis of the study results

On horizontal surface, our study results reveal that on overall, users are more efficient with our techniques (Arm and Head-To-Finger) than with the Direct Pointing technique. This remains true with any combination of target size and distance except with the Far Small ones with which no significant difference can be observed. This combination corresponds to the most difficult situation and may point out the difficulties of pointing at a target situated on the edge of the human field of vision. Our technique Head-To-Finger is the best in terms of target crossings, demonstrating its ability to support precise target pointing. We found no significant difference across techniques in terms of user preference or perceived task load.

On the vertical surface, although Direct Pointing performs better overall than Arm and Head-To-Finger, results show that no significant difference can be established between Direct Pointing and Head-To-Finger when considering the different combinations of target size and distances separately. Furthermore, Direct Pointing performs better than Arm in only one of these four combinations (Far Small). In terms of target crossings, no significant difference was found between Head-To-Finger and Direct Pointing, but both performed better than the Arm technique. Users preferred Direct Pointing over the Arm technique, and it was perceived to require less effort. Nevertheless, there was no significant difference in terms of preference or perceived task load between Direct Pointing and Head-To-Finger.

About hand's height, our study reveals that our techniques require the users to raise their hands higher than with the Direct Pointing technique on both surfaces. However, Direct Pointing requires users to move their heads towards the target. We believe that this explains the absence of difference between Head-To-Finger and Direct Pointing in terms of ranking or perceived task load for both surfaces: the effort associated with raising the hand is compensated by the absence of head movements.

We also believe that the hand's height result contributes to explaining the difference in the performance of our techniques between vertical and horizontal surfaces. Indeed, when using our techniques, users have to raise their arms higher on vertical surfaces than on horizontal surfaces: this can explain why the best technique on horizontal surfaces, Head-To-Finger, is not as efficient on vertical surfaces. We provide some ideas on how to improve this technique in the Perspectives section.

To sum up, the Head-To-Finger technique is the most efficient solution on horizontal surfaces in three Size x Distance conditions out of four, and performs similarly in the fourth one. This conclusion holds in terms of completion time and target crossings. On a vertical surface, whatever the Size x Distance condition, results do not establish any difference between the Head-To-Finger technique and the Direct Pointing technique, in terms of completion time, crossing and preferences.

The results of our study thus suggest that the Head-To-Finger technique is a good compromise for pointing at physical referents out the HMD FoV on horizontal and vertical conditions.

As opposed to horizontal surfaces, we believe that Head-To-Finger does not perform better than the others on vertical surfaces, because of the required eyes and head movements involved: targets located down require fewer head movements than targets located on the left, right, and up [45]. As a result, when using Head-To-Finger on vertical surfaces, head movements are more frequent and ample than on horizontal surfaces, reducing the difference in completion time with Direct Pointing and slightly impacting the order of preference for these two techniques.

5.2 Impact of our results on the usage scenarios

Augmented Physical Model for data analysis. In this scenario, the physical model is placed on a horizontal table, and Alice, the urban planner, has to point at small targets on the table. The typical size of the physical model of a district, campus or building is generally below one meter, thus placing the targets Near the user. Hence, given the results of the studies, the Direct Pointing technique should be avoided because it performs less efficiently than the two others for Near targets. A pointing technique specifically designed for pointing at targets around the FoV, is thus recommended. Our techniques, using a focus view, should therefore be preferred. It may be the Arm technique, embedded in the HoloLens 2 device, or the Head-To-Finger technique, the latter minimizing the risk of target crossings. This design would also maximize the efficiency with larger targets, such as buildings or parks.

Logistic management. In this scenario, the products are placed on vertical shelves, and Daniel, the logistics operator, has to point at large targets on the shelves. Given the results of the studies, the Arm technique, available in the HoloLens 2, should be avoided because it induces more efforts than the Direct Pointing technique. Using the Direct Pointing technique, Daniel moves his head up, down, right, and left to look at the successive products and is able to directly point at them to access associated data. While this technique minimizes arm movement, it requires frequent head motions, which can lead to fatigue and momentarily shift focus away from the data. Given that no clear difference was identified between Direct Pointing and the Head-To-Finger technique in terms of preferences, using Head-To-Finger would minimize these uncomfortable head movements. Indeed, with the Head-To-Finger technique, Daniel moves his finger to select targets in his field of vision, while keeping the relevant data in the HMD FoV right in front of him. Although both techniques offer similar performances in terms of completion times, Head-To-Finger is particularly recommended when interacting with shelves of reduced height, as it will avoid raising the arm too high, whereas Direct Pointing would be more appropriate when accessing products on tall shelves: looking high above the head is more comfortable than raising the arms above the shoulders on the left or right of the head [1].

5.3 Limitations

First, our participant sample consisted of 12 young computer scientists. While such a size and distribution are common in HCI experiments with similar homogeneous samples, it limits the generalizability of our results to the broader population.

Second, on vertical surfaces, our techniques need to be improved to perform better than Direct Pointing for difficult targets (far, small). As observed during our study, users raise their arms high when pointing at targets on a vertical surface in front of them. Therefore, we suggest that an area of improvement is to limit these movements by using indirect pointing techniques, such as ARPads [10], by defining input zones on the user's body.

Third, tracking the hands with an infrared optical system prevents an ecological use or transfer of our techniques into a real application. Some recent developments, such as the HOOV system [46], could allow for a real-world implementation of our techniques. Third, the set of participants included only male and female college computer science students. We plan to perform further studies with participants having a broader background and range of familiarity with AR technologies.

5.4 Perspectives

Beyond these results, several perspectives emerge from our study. First, it has been observed that users, whether using the Head-To-Finger or Arm technique, combine a direct and indirect view of targets to perform pointing tasks effectively. In light of this observation, the question arises as to the level of mismatch of different viewpoints that the user can manage for a pointing task. In practice, future studies should explore an adaptation of the Head-To-Finger technique to display, in the focus view, a perspective from behind the targets, particularly in the context of pointing at partially or totally occluded targets.

Next, in our design, the focus view position is static at the center-bottom of the HMD FoV. In the horizontal setting, this placement is convenient since users naturally look at the bottom to see the objects. However, this position might not be optimal for the vertical setting. An alternative approach could be to dynamically reposition the focus view according to the user's gaze direction, allowing it to switch between three predefined positions (left, right, and center-bottom).

In addition, our study focused on pointing at physical referents located around the HMD FoV. Although the classical raycasting technique is recognized as an effective method for pointing at targets within the HMD FoV, it would be relevant to consider pointing at targets alternatively in and around the HMD FoV. This would lead to studying transitions between different pointing techniques in these areas, thus providing a more complete perspective on our usage scenarios.

Other AR contexts beyond Situated Visualization are subject to problems related to the narrow FoV of HMDs. They could benefit from our techniques to point at surrounding physical objects without requiring the user to move their head, such as when interacting with smart objects populating the environment or exploring augmented museum exhibits. We will further investigate the interest of our techniques in these other application areas.

Finally, although our techniques are designed explicitly for pointing at physical referents that are directly visible to the user but cannot be augmented, the question arises as to whether these techniques can be applied to pointing outside the human FoV. This question opens the way to future research to evaluate our techniques' effectiveness in contexts where the target is in a cluttered environment or is not visible, i.e. can be located inside a physical referent (a part of a building, for example) or outside the human FoV.

6 Conclusion

In this paper, we addressed the specific challenge of pointing at physical targets around the HMD FoV, but in the user's field of vision. We designed and evaluated two original techniques the Arm and Head-To-Finger techniques, based on displaying a focus view in which is reproduced an area centered on the ray's impact point. In three out of four Distance x Size conditions, our results established that the Head-To-Finger technique is more efficient than the Arm and the Direct Pointing techniques to point at physical targets distributed on a horizontal surface, and performs equally in the fourth condition. Our techniques also perform similarly to the Direct Pointing technique on vertical surfaces because they require a too ample motion with the arm.

Our work is the first exploration of the challenge of pointing at physical targets around the HMD FoV, a crucial question given the limited FoV of optical see-through HMDs. We expect our exploration to open up future research related to this challenge, for which we discussed several short and middle-term perspectives.

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APPENDICES

A.1 Completion time per surface and technique

Table 1. Completion time on the horizontal surface per technique

Horizontal	$\chi2(2) = 15.17, p = 0.0005$			
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.39	[5.19, 5.61]	Head-To-Finger	Z = 7.91, p < 0.0001
Arm	4.72	[4.50, 4.99]	Direct Pointing	Z = 6.94, p < 0.0001
Head-To-Finger	4.4	[4.22, 4.61]	Arm	Z = 1.93, p = 0.16

Table 2. Completion time on the vertical surface per technique

Vertical	$\chi2(2) = 8, p = 0.018$			
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.38	[5.19, 5.60]	Head-To-Finger	Z = 2.87, p = 0.012
Arm	7.45	[6.94, 8.07]	Direct Pointing	Z = 4.51, p < 0.0001
Head-To-Finger	6.47	[6.10, 6.91]	Arm	Z = 2.32, p = 0.061

A.2 Completion time per surface, technique, target size and distance

Table 3. Completion time on the horizontal surface per technique, target size and distance

Horizontal	$\chi2(2) = 18.5, p < 0.0001$			
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	4.88	[4.55, 5.32]	Head-To-Finger	Z = 4.41, p < 0.0001
Arm	3.68	[3.39, 4.11]	Direct Pointing	Z = 6.76, p < 0.0001
Head-To-Finger	4.15	[3.78, 4.63]	Arm	Z = 2.76, p = 0.017
Horizontal	$\chi2(2) = 12.5, p = 0.0019$			
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.23	[4.9, 5.63]	Head-To-Finger	Z = 4.18, p < 0.0001
Arm	4.69	[4.37, 5.12]	Direct Pointing	Z = 2.93, p = 0.01
Head-To-Finger	4.59	[4.2, 5.08]	Arm	Z = 1.19, p > 0.01
Horizontal	$\chi2(2) = 15.5, p = 0.0004$			
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.61	[5.18, 6.1]	Head-To-Finger	Z = 6.94, p < 0.0001
Arm	4.41	[4.05, 4.89]	Direct Pointing	Z = 5.57, p < 0.0001
Head-To-Finger	4.06	[3.75, 4.46]	Arm	Z = 2.50, p = 0.037
Horizontal	$\chi2(2) = 2.17, p > 0.05$			
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.84	[5.47, 6.28]	Head-To-Finger	
Arm	6.11	[5.51, 6.85]	Direct Pointing	
Head-To-Finger	4.81	[4.47, 5.19]	Arm	

Table 4. Completion time on the vertical surface per technique, target size and distance

Vertical			$\chi2(2) = 0.67$, $p = 0.72$	
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	4.84	[4.52, 5.26]	Head-To-Finger	
Arm	6.05	[5.34, 7.11]	Direct Pointing	
Head-To-Finger	5.4	[4.92, 5.99]	Arm	
Vertical			$\chi2(2) = 6.17$, $p = 0.046$	
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.37	[5.08, 5.76]	Head-To-Finger	$Z = 2.38$, $p = 0.053$
Arm	7.07	[6.26, 8.11]	Direct Pointing	$Z = 1.62$, $p = 0.318$
Head-To-Finger	7.21	[6.4, 8.33]	Arm	$Z = 0.63$, $p = 1$
Vertical			$\chi2(2) = 5.17$, $p = 0.076$	
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.42	[5.03, 5.96]	Head-To-Finger	
Arm	6.48	[5.82, 7.3]	Direct Pointing	
Head-To-Finger	6.17	[5.42, 7.2]	Arm	
Vertical			$\chi2(2) = 9.5$, $p = 0.0086$	
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	5.9	[5.53, 6.4]	Head-To-Finger	$Z = 1.99$, $p = 0.14$
Arm	10.21	[8.78, 12.14]	Direct Pointing	$Z = 4.30$, $p < 0.0001$
Head-To-Finger	7.11	[6.41, 7.99]	Arm	$Z = 3.46$, $p = 0.002$

A.3 Hand's height per technique and surface

Table 5. Hand's height on the horizontal surface per technique

Horizontal			$\chi2(2) = 16$, $p = 0.0003$	
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.73	[-0.73, -0.71]	Head-To-Finger	$Z = 15.21$, $p < 0.0001$
Arm	-0.57	[-0.58, -0.56]	Direct Pointing	$Z = 14.62$, $p < 0.0001$
Head-To-Finger	-0.46	[-0.48, -0.45]	Arm	$Z = 15.03$, $p < 0.0001$

Table 6. Hand's height on the vertical surface per technique

Vertical			$\chi2(2) = 16$, $p = 0.0003$	
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.65	[-0.67, -0.64]	Head-To-Finger	$Z = 15.51$, $p < 0.0001$
Arm	-0.07	[-0.09, -0.04]	Direct Pointing	$Z = 15.51$, $p < 0.0001$
Head-To-Finger	0.03	[0.01, 0.06]	Arm	$Z = 14.18$, $p < 0.0001$

A.4 Hand's height per surface, technique, target size and distance

Table 7. Hand's height on the horizontal surface per technique, target size and distance

Horizontal		$\chi2(2) = 14.25$, $p = 0.0008$		
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.73	[-0.74, -0.69]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.62	[-0.63, -0.61]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	-0.52	[-0.54, -0.5]	Arm	Z = 2.38, p = 0.047
Horizontal		$\chi2(2) = 16$, $p = 0.0003$		
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.73	[-0.74, -0.71]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.52	[-0.53, -0.51]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	-0.4	[-0.42, -0.38]	Arm	Z = 2.52, p = 0.023
Horizontal		$\chi2(2) = 14.25$, $p = 0.0008$		
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.72	[-0.74, -0.7]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.62	[-0.63, -0.61]	Direct Pointing	Z = 2.24, p = 0.07
Head-To-Finger	-0.54	[-0.56, -0.53]	Arm	Z = 2.52, p = 0.023
Horizontal		$\chi2(2) = 14.25$, $p = 0.0008$		
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.72	[-0.74, -0.7]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.52	[-0.53, -0.51]	Direct Pointing	Z = 2.38, p = 0.047
Head-To-Finger	-0.38	[-0.4, -0.36]	Arm	Z = 2.52, p = 0.023

Table 8. Hand's height on the vertical surface per technique, target size and distance

Vertical		$\chi2(2) = 14.25$, $p = 0.0008$		
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.65	[-0.67, -0.62]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.04	[-0.08, -0.01]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	0.06	[-0.02, 0.1]	Arm	Z = 2.52, p = 0.023
Vertical		$\chi2(2) = 16$, $p = 0.0003$		
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.65	[-0.68, -0.62]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.1	[-0.15, -0.04]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	0	[-0.05, 0.05]	Arm	Z = 2.38, p = 0.047
Vertical		$\chi2(2) = 14.25$, $p = 0.0008$		
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.66	[-0.69, -0.62]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.04	[-0.08, 0]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	0.06	[0.03, 0.1]	Arm	Z = 2.52, p = 0.023
Vertical		$\chi2(2) = 14.25$, $p = 0.0008$		
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	-0.64	[-0.67, -0.61]	Head-To-Finger	Z = 2.52, p = 0.023
Arm	-0.09	[-0.08, -0.04]	Direct Pointing	Z = 2.52, p = 0.023
Head-To-Finger	0	[-0.03, -0.1]	Arm	Z = 2.52, p = 0.023

A.5 Number of target crossing per surface and technique

Table 9. Number of target crossing on the horizontal surface per technique

Horizontal		$\chi2(2) = 10.5$, $p = 0.005$		
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.96	[1.83, 2.11]	Head-To-Finger	Z = 5.48, p < 0.0001
Arm	2.05	[1.90, 2.34]	Direct Pointing	Z = 0.62, p = 1
Head-To-Finger	1.54	[1.45, 1.67]	Arm	Z = 7.11, p < 0.0001

Table 10. Number of target crossing on the vertical surface per technique

Vertical		$\chi2(2) = 13.17$, $p = 0.001$		
	Mean	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.66	[1.58, 1.76]	Head-To-Finger	Z = 1.04, p = 1
Arm	2.55	[2.32, 2.89]	Direct Pointing	Z = 6.20, p < 0.0001
Head-To-Finger	1.67	[1.57, 1.79]	Arm	Z = 7.01, p < 0.0001

A.6 Number of target crossing per surface, technique, target size and distance

Table 11. Number of target crossing on the horizontal surface per technique, target size and distance

Horizontal		$\chi2(2) = 7.41$, $p = 0.025$		
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.67	[1.5, 1.89]	Head-To-Finger	Z = 3.81, p = 0.0005
Arm	1.46	[1.34, 1.58]	Direct Pointing	Z = 1.35, p = 0.435
Head-To-Finger	1.28	[1.18, 1.41]	Arm	Z = 3.09, p = 0.057
Horizontal		$\chi2(2) = 3.11$, $p = 0.21$		
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.68	[1.48, 1.98]	Head-To-Finger	
Arm	1.95	[1.73, 2.31]	Direct Pointing	
Head-To-Finger	1.68	[1.47, 2.17]	Arm	
Horizontal		$\chi2(2) = 11.87$, $p = 0.0026$		
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	2.14	[1.88, 2.46]	Head-To-Finger	Z = 4.58, p < 0.0001
Arm	1.89	[1.71, 2.1]	Direct Pointing	Z = 1.19, p = 0.62
Head-To-Finger	1.42	[1.28, 1.58]	Arm	Z = 4.25, p < 0.001
Horizontal		$\chi2(2) = 6.39$, $p = 0.041$		
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	2.34	[2.03, 2.8]	Head-To-Finger	Z = 2.42, p = 0.043
Arm	2.91	[2.46, 4.12]	Direct Pointing	Z = 1.58, p = 0.22
Head-To-Finger	1.8	[1.6, 2.08]	Arm	Z = 4.84, p = 0.0001

Table 12. Number of target crossing on the vertical surface per technique, target size and distance

Vertical	$\chi2(2) = 2.84$, $p = 0.24$			
Large Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.53	[1.41, 1.66]	Head-To-Finger	
Arm	1.61	[1.43, 1.86]	Direct Pointing	
Head-To-Finger	1.45	[1.29, 1.78]	Arm	
Vertical	$\chi2(2) = 12.88$, $p = 0.0016$			
Large Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.55	[1.43, 1.69]	Head-To-Finger	$Z = 0.32$, $p = 1$
Arm	2.41	[2.11, 2.97]	Direct Pointing	$Z = 3.60$, $p < 0.001$
Head-To-Finger	1.55	[1.41, 1.7]	Arm	$Z = 3.93$, $p < 0.0001$
Vertical	$\chi2(2) = 4.33$, $p = 0.12$			
Small Near	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.73	[1.57, 1.93]	Head-To-Finger	
Arm	2.66	[2.18, 4.03]	Direct Pointing	
Head-To-Finger	1.68	[1.52, 1.88]	Arm	
Vertical	$\chi2(2) = 11.26$, $p = 0.0036$			
Small Far	**Mean**	**CI**	**Compared to**	**Wilcoxon**
Direct Pointing	1.83	[1.63, 2.18]	Head-To-Finger	$Z = 0.74$, $p = 1$
Arm	3.53	[3.03, 4.3]	Direct Pointing	$Z = 5.69$, $p < 0.0001$
Head-To-Finger	1.99	[1.75, 2.31]	Arm	$Z = 4.67$, $p < 0.0001$