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Design and Evaluation of an “Around the SmartPhone” Technique for 3D Manipulations on Distant Display

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ABSTRACT

In this paper, we present the “Around the SmartPhone” interaction technique for manipulating 3D elements displayed on a distant screen. The design of the technique is based on the selection of the most appropriate value for characteristics useful to discriminate existing tactile and tangible techniques for 3D manipulations. We perform two user studies to compare this around-device technique for translating and rotating 3D objects, with two existing tangible and tactile solutions, in terms of performance and user’s preference. The literature establishes that the tactile technique evaluated is the best tactile technique among the existing tactile techniques for 3D manipulation. Despite this result, our user study reveals that the two others perform significantly better. In addition, when feedback visibility is preserved, the around-device technique offers similar performance results than the tangible one. Finally, the around-device technique is significantly preferred over the two others in every condition.

Keywords

3D interaction; manipulation task; around-device interaction.

1. INTRODUCTION

Using 3D content in interactive environment is becoming more and more frequent. 3D interactive virtual environments (3DVE) tend to get out of the sole hands of 3D experts using dedicated devices [11]. Indeed 3DVE can now be found in many private activities such as on web sites to assist house furniture selection [23], in daily mobile contexts [25] and to play public 3D games [41]; in professional contexts to visualize scientific 3D data [38], to explore 3D data during meetings [16] or to create and edit 3D model [2]; and even in museums [29].

Using a smartphone for supporting the interaction with 3DVE in such everyday life situations presents many potential benefits: providing a multi-sensor remote interaction control thus avoiding occlusion; exploiting a personal and familiar device; displaying additional feedback on the smartphone screen. The use of

smartphone to interact with 3D content on distant display has already been considered for example to manipulate a slice plane [38], to navigate, select or manipulate a 3D object [5, 21, 23]. Combinations of finger movements [39], device orientations [23] and gesture around the device [21] represent many alternatives for implementing smartphone-based techniques for 3D interaction.

Among these works, less attention has been paid to the combined use of around-device techniques, based on a smartphone, with a 3D scene displayed on a distant screen. And yet, “around the smartphone” interaction techniques have already been successfully explored in other settings [17, 20]. The goal of our work is thus to design, implement and evaluate a new interaction technique involving gestures around a smartphone to manipulate a 3D object displayed on a distant screen.

We first review existing smartphone-based interaction techniques with 3D environments displayed on the smartphone and on distant screens. Secondly, we describe a tangible and a tactile smartphone-based interaction technique to manipulate 3D objects: each one is representative of one of these two classes of existing interaction techniques based on a smartphone in such 3D task. We then describe four characteristics related to the specificities of the context and through which existing tactile and tangible techniques can be analyzed and discriminated. Based on these characteristics, we design a new technique, “Around the SmartPhone” (ASP), which involves hand gestures around the smartphone to manipulate 3D elements displayed on a distant screen. A first user study with training session and a complementary user study ensuring a more realistic use of the smartphone, compare the three techniques in terms of performance, usability and user’s preference. Results reveal that our around-device technique (ASP) performs far better than the tactile solution (OSP). Moreover, ASP technique offers equivalent performance than the tangible solution (WSP). In addition, ASP is largely identified as the preferred technique among the three considered.

2. RELATED WORK

Many interaction techniques exist in virtual reality (VR) to support 3D manipulations (i.e. 3D elements translations and rotations), such as World-in-Miniature, Virtual Hand or Go-Go techniques [6]. More advanced forms of interaction include tangible interfaces such as the Hinckley’s puppet [14] and the Cubic Mouse [10]. In this section, we specifically focus on other advanced interaction techniques in which smartphones have been involved to manipulate 3D objects.

Given the growing computing capabilities of smartphones, 3D content can easily be displayed and interacted with, on a smartphone. A first trend for supporting 3D manipulations consists in using the direct touch modality, i.e. the tactile screen [15]. Based on an adaptation of multi-touch and direct interaction on tabletop, different techniques have been proposed such as the Z-technique [27], useful to translate an object and the Arc-Ball [32] technique useful to rotate an object. Both have been

implemented on smartphone [39] and compared to the Dual-Finger technique to manipulate 3D objects. Indirect manipulations through the use of widgets for controlling 3D manipulation have also been developed [8] or adapted from existing widget [21]. One important result related to touch based interaction with 3D is that the separation of Degrees Of Freedom (DOF) increases the performance of 3D manipulations [26]: three touch techniques perform better than one or two single touch techniques [13].

Alternatively, smartphones also integrate multiple sensors that have been used to design new forms of interaction: these forms of interaction can be considered as tangible interfaces. Orientation of the device combined with the use of the touch-screen can be used to manipulate a 3D object [9, 24].

A third set of researches aims to cope with the size of the screen and has therefore investigated around-device interaction technique as a novel approach to interact with 3D content. PalmSpace is a mid-air gesture technique for rotating 3D objects displayed on the smartphone screen [21]. In T(ether) [22], multi-user 3D modeling and animation are supported through gestures above, behind and on a tablet surface. Mid-air gestures have also been explored to support the navigation and the selection of 3D objects [5]. Even more prospectively the combination of mid-air interaction and rendering around a smartphone has been explored to create a true-3D interactive projection [36].

In the works previously mentioned, the 3DVE is displayed on the smartphone screen. But using a smartphone for interacting with 3D content has also been considered in combination with a distant screen: the smartphone becomes a remote controller of the 3D content. In such settings the smartphone has been used to support single touch interaction while exploring and manipulating distantly displayed cultural heritage 3D models [29]. Other works made use of the smartphone to allow the combination of tactile interaction and smartphone movements for controlling a 3D object with a virtual hand [19, 23] on the remote screen. Tangible use of a smartphone for rotating 3D distant element has also been investigated [18]. Different approaches considered the smartphone as a tool palette to explore and annotate 3D medical data [38], or as a carrier artefact to select and share object between several displays, tabletops or other smartphones during meetings [16].

To summarize, we observe that tactile, tangible and around-device solutions have been proposed in the literature to support user's interaction with 3DVE. However, only tactile and tangible solutions have been proposed to support user's interaction based on a smartphone with a 3DVE displayed on a distant screen. And yet, around-device solutions have been identified as promising for tasks in which multiple degrees of freedom must be controlled simultaneously [21].

Our goal is thus to build upon this opportunity and fill the gap left in the existing works by designing and developing an around-device interaction technique, based on a smartphone, for manipulating 3DVE displayed on a distant screen. Among the well-known 3D tasks [6], we focus in this paper on the manipulation task only because this task is more complex as it definitely requires the 6DOF to be controlled.

3. CHARACTERISTICS DISCRIMINATING TACTILE AND TANGIBLE INTERACTION TECHNIQUES

We first present the implementation of two interaction techniques, representative of the tactile and tangible sets of existing smartphone-based techniques for manipulating 3DVE on a distant screen. "With the SmartPhone" (WSP) is a tangible interaction

with the mobile device itself, and is similar to tangible interface [10, 14]; "On the SmartPhone" (OSP) is a tactile technique which requires finger gestures to be performed on the smartphone just as in DualFinger [39]. They both constitute a reference among existing interaction techniques for 3D manipulation: WSP corresponds to a very common tangible situation, well known and also validated for its usability [14, 37]; OSP being an implementation of the Dual-Finger technique based on its authors original code, it has been established that OSP, like the original, offers better performance than other tactile applications [39].

To analyze and compare these two sets of interaction techniques we identified four discriminating characteristics. They correspond to design questions that should be raised to design interaction techniques for manipulating 3D on a distant screen: input frame of reference; DOF combination abilities; feedback visibility; and available space in input. We describe the role and possible values of each characteristic, and illustrate them on WSP (tangible) and OSP (tactile).

3.1 A Tangible (WSP) and Tactile (OSP) Implementations of Existing 3D Manipulation Techniques

The tangible technique is the "With the SmartPhone" (WSP) technique. The behavior of this technique (Figure 1) is very similar to the one described in [14] to manipulate a cutting plane in 3D medical data. Translation offsets of the smartphone are measured in a coordinate system defined by the distant display and directly mapped to the manipulated elements of the 3D scene. Similarly, any rotations of the smartphone are directly mapped to rotations applied to the selected 3D object. For example rotating the smartphone in a plane parallel to the ground, triggers rotations of the 3D object around its vertical axis (Y axis). Such tangible approaches have been very frequently adopted in virtual reality settings with various physical props. Here the prop is the smartphone that embeds a display and other sensors. In addition, tangible interfaces have been proven to be easy to apprehend by newcomers and occasional users [37].

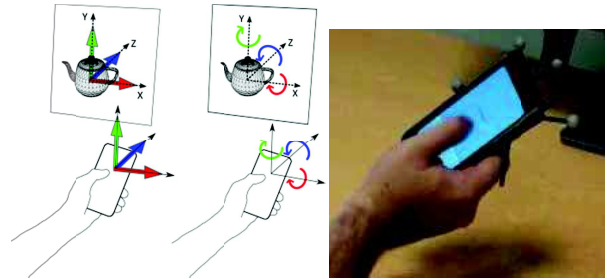


Figure 1. WSP behavior (translation, rotation) and in use. Colored arrows: input and 3D object movements. Black arrows: input (thin) and 3D (dashed) frame of reference.

The tactile technique is the "On the SmartPhone" (OSP) technique (Figure 2): it is an implementation of the Dual-Finger technique [39]. To perform a translation, if the two fingers are moved jointly up and down on the screen, the 3D manipulated object moves along the Y axis of the 3D scene. If the two fingers are moved apart, the plane defined by the smartphone display is mapped to the (X, Z) plane of the 3D scene, i.e. the ground of the virtual environment. To perform a rotation task, we quote [39]: "When the user moves both fingers parallel to X axis in the same direction, the object is correspondingly rotated around the Y axis. The same applies to moving the fingers parallel to Y axis in the same direction to rotate the object around X axis. Rotation

around Z axis is performed by a twisting action by moving the fingers parallel to X axis or Y axis, in the opposite direction". It was established that Dual-Finger has better performance [39] in comparison to other well-known tactile interaction technique, e.g. the Z-technique [27] and the Arc-Ball [32] technique.

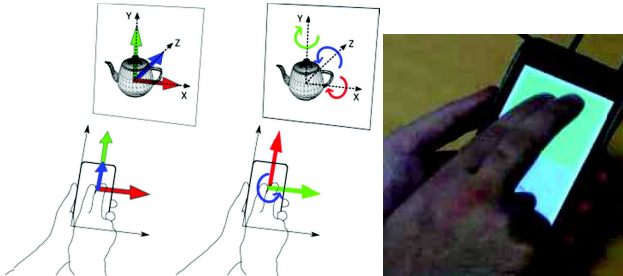


Figure 2. OSP behavior (translation, rotation) and in use.
Arrows: same conventions than Figure 1.

3.2 Four discriminating characteristics

We here describe and illustrate four discriminating characteristics to analyze and compare WSP and OSP that according to the literature may play a role in the usability of the techniques.

A well-known design question in 3D is related to the coordinate system according to which transformations will be applied to elements of the 3D scene. The 3D scene frame of reference represents the frame of reference adopted to apply rotations and translations to rendered elements of a 3D environment [42]. The *egocentric frame of reference* corresponds to a viewer's perspective: it is centered at the user's head. The *room-centered frame of reference* (usually called the world reference) or extrinsic frame refers to unchanging environmental settings: it is based on an absolute reference, fixed in the environment. The *object frame of reference*, or intrinsic frame, refers to the top, bottom, left, right of an object: it is attached to the 3D object manipulated.

Regarding WSP and OSP, the 3D scene frame of reference adopted is the world reference, i.e. the most usual one used in virtual reality settings. Therefore, it is not one of the discriminating characteristics but it is tightly linked to the first one: the input frame of reference.

The **input frame of reference** denotes the frame of reference in which user's inputs are performed to manipulate elements of a 3D scene. Poupyrev notions of *exocentric* and *egocentric* metaphors [34] for manipulation techniques slightly express this consideration. Through the combination of the *Display centricity* and the *Control-Display congruence* axis [31], Milgram better emphasizes the need for considering not only the 3D scene frame of reference but also the frame of reference in which user's controls are initiated. Ware [42] provided an even clearer definition by introducing the *haptic* frame of reference in which the input device used by the user is manipulated. He also shows the importance of adopting a coherent combination of a 3D scene frame of reference and haptic frame of reference.

Regarding WSP, moving the smartphone parallel to the distant display and to its right moves the manipulated 3D objects to the right of the 3D scene. Same behavior applies along the other axis and for the rotations. The input frame of reference is then aligned with the 3D scene frame of reference, i.e. the world reference. Regarding OSP, sliding the finger to the right of the smartphone display moves the manipulated 3D object to the right of the 3D scene. The input frame of reference is therefore attached to the smartphone display. As this display defines only 2DOF, a metaphoric mapping defines a reference for the third rotation

(rotations of two fingers) and an arbitrary mapping defines a reference for the third translation (joint fingers instead of fingers apart).

DOF combination ability has an impact on 3D digital tasks. As synthesized in [28] using real object to manipulate 3D elements is quicker than using traditional mouse and keyboard, but simultaneous use of all the DOF does not always lead to the best performance in virtual reality settings. It was also established that separating translation and rotation significantly and positively affects performance [26].

Regarding WSP and OSP, rotations and translations are totally separated: it is impossible to perform them simultaneously in the present setting. WSP allows the three axes to be controlled simultaneously during translations or rotations. With OSP, translation along the Y axis (joint fingers) can only be used separately and rotation can be performed along one axis only at a time.

Feedback visibility is one huge benefit of involving a smartphone in such settings instead of physical props as in [14]. The smartphone screen can provide the user with different forms of feedback: a 3D detail of the distant scene as in [5], a textual feedback about the accurate position and orientation of the 3D object, annotations or real pictures of different parts of the 3D scene, etc. In those cases it is important to maintain eye-access to the smartphone screen since it may affect the user's task.

Regarding WSP, the feedback visibility is not always maintained: if the smartphone is translated too far away from the user and under certain combinations of rotations of the devices handed by the user, the display is no longer readable or even visible. Regarding OSP, the traditional finger occlusion issue is raised. Feedback visibility is only partially maintained.

Available space in input varies among smartphones and tablets sizes, but comes with a higher weight and delicateness, not compatible with public spaces and mobile devices. Alternatively exploiting the space all-around the devices extends the available space in input and for example efficiently supports input vocabulary on smartphone [20]. Available input space can thus significantly affect the usability.

Regarding WSP, the available space is almost unlimited. It is just constrained by wrist movement (rotation) and by the size of the user's arm (translation). Regarding OSP, the space is limited to the size of the smartphone screen.

4. DESIGNING THE "AROUND THE SMARTPHONE" TECHNIQUE

In this section, we present the design of the "Around the SmartPhone" (ASP) technique, an around-device technique based on a smartphone and dedicated to the manipulation of a 3D scene rendered on a distant display.

4.1 ASP in Brief

ASP is a smartphone based technique used to manipulate 3D elements displayed on a distant screen. With ASP the user steadily handles the smartphone in the non-dominant hand and performs hand gestures, with the dominant hand, around the smartphone. Translating (resp. rotating) the dominant-hand around the smartphone controls the translation (resp. orientation) of the 3D manipulated object.

Unlike PalmSpace [21] user's hand gestures around the smartphone are not limited to the control of rotations. In addition, our ASP technique is not dedicated to situation in which 3D scene

is displayed on the smartphone and mid-air gesture can be continuously produced all around the device.

Another technique similar to ASP was proposed in [5] for a selection task performed in a 3D scene. ASP however is not limited to translations of a single plane and allows different forms of feedback to be displayed on the smartphone screen without restricting it to a detailed portion of the 3D scene. Mid-Air Hand [5] and ASP also differ in terms of control (respectively absolute and relative).

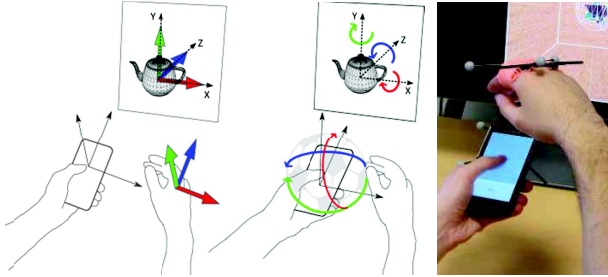


Figure 3. ASP behavior (translation, rotation) and in use.
Arrows: same conventions than Figure 1.

In comparison to the tactile and tangible techniques introduced above, our ASP technique and the WSP technique are based on the use of mid-air gestures while the OSP technique is a traditional on-screen interaction technique. However, WSP technique involves writ movements while ASP technique involves hand and arm movements around the smartphone thus offering larger mid-air gesture amplitude.

To further refine the design of ASP, we now refer to the four discriminating characteristics introduced and illustrated on WSP and OSP, and instantiate them in a suitable manner to fit the around-device setting (cf. Table 1).

4.2 Optimizing the four discriminating characteristics

Input frame of reference: ASP being used in front of a distant screen, the user may be not perfectly facing the screen. Therefore adopting the world reference as input frame might be disturbing: if the user looks at the screen with an angle of 45 degrees, hand motions would still have to be performed perpendicularly or parallel to the distant screen!

The goal of ASP is to offer a solution supporting the lack of alignment between the devices used to render the 3D scene and produce the input controls, i.e. to support the use of two different frames of reference for the 3D scene (world reference) and the input (smartphone reference). Therefore, the input frame of reference of ASP must be attached to the smartphone as in OSP. However unlike OSP, it is a true 3DOF input frame of reference not limited to the smartphone-display axes: the third axis is perpendicular to the smartphone screen. It adds a benefit: the user can adjust the position and orientation of the non-dominant hand handling the smartphone in order to allow more comfortable movements of the dominant hand around the smartphone.

As a result, for the translation task (Figure 3), translation offsets of the dominant hand are thus computed with regards to the smartphone orientation and applied to the 3D object.

For the rotation task (Figure 3), the smartphone (resp. its center) materializes the axes (resp. the origin) of the input frame of reference around which hand rotation offsets are measured and then applied to the 3D object.

DOF combination abilities: as previously mentioned, separating translations and rotations leads to better performance. Furthermore even if both translation and rotation can be performed jointly users usually perform them independently [30]. We therefore chose for the ASP technique to keep the translation and rotation separated as in WSP and OSP techniques. In addition, we choose to support the combination of the three axes when performing translation (resp. rotations): this is similar to the WSP technique and better takes advantage of the spatial interaction capabilities offered by the around-device setting.

Feedback visibility: since ASP relies on gestures performed around the smartphone, the feedback visibility will by construction be maximized. In very limited situations, the dominant arm or hand may occlude the screen from the user's-eye. However head inclinations will overcome these limitations. Among the three considered techniques, ASP supports the largest feedback visibility.

Available space in input: when designing ASP, it appeared that the available space in input is slightly different from the available space in WSP: arm size is again constraining the translations movement, but for the rotation, the technique is constrained by the user's motor ability to move the dominant hand and arm around the smartphone.

Table 1. Discriminating characteristics applied to ASP, WSP and OSP (gray = value is different from ASP)

	ASP	WSP	OSP
Input frame of ref.	smartphone (case - 3D)	world reference	smartphone (display - 2D)
DOF combination	T: 3; R: 3	T: 3; R: 3	T: 2 or 1; R: 1
Feedback visibility	always	limited by device orientation	limited by finger occlusion
Available input space	T: arm size R: arm constraint	T: arm size R: wrist constraint	T: display size R: display size

5. FINALIZING THE IMPLEMENTATION OF ASP, WSP AND OSP

Additional design issues, common to any interaction technique, have been considered to finalize the implementation of the three techniques. They are not specific to a smartphone based interaction technique to manipulate 3DVE displayed on a distant screen but they guided the final implementation of the techniques.

3D tasks, mode switching. In the three techniques, manipulation includes 3D translations and 3D rotations which can only be performed separately (cf. section on DOF combination abilities). A mode switching mechanism is thus integrated: the user must press a button, displayed on the smartphone, during the action (translation or rotation).

Control mode. Interaction with (WSP), on (OSP), or around (ASP) the smartphone does not provide any force feedback. These techniques can therefore be considered as isotonic and position control of the cursor is preferable [43].

C/D gain. Control-Display gain is a recurrent design consideration in HCI community [7]. Two major approaches exist: the ratio can be constant or computed on the basis of a mathematical function applied to movement characteristics. Typically this consideration raises a trade-off between speed and accuracy. The three techniques considered in this paper adopt a constant C/D gain. Regarding WSP, tangible UI physical manipulations are directly applied to the digital world and cannot

be accelerated. Regarding ASP, using a constant C/D gain simplifies the use of the technique and limits the learning difficulties. A one to one C/D gain for ASP and WSP is thus used. Now regarding OSP, adopting a constant C/D gain is conform to the initial implementation of the technique [39]: to fit with the 3D environment used in our user study, the adopted C/D gain resulted from a preliminary study allowing the users to adjust the C/D gain to allow a comfortable use of the technique.

Gesture mapping and clutching mechanism. Kratz [21] defined four different mappings of hand gestures onto the orientation of a virtual object, that are also applicable to the translation task: absolute control, scaled absolute control, relative control and rate control. The three techniques considered adopt a relative control. This is again in line with the implementation of OSP provided by the authors. Regarding WSP and ASP a relative control induces the presence of clutching and provides more fluidity in the manipulation: whatever the initial position and orientations of the manipulated object, it can be further translated or rotated without having to reposition the dominant hand in the previously reached configuration.

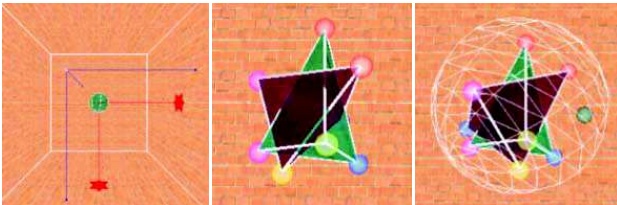


Figure 4. Visual aids in the 3D scene for the translation (left) and rotation task (center and right).

Visual aids. Many works explored visual aids for guiding and helping the user during the interaction process [6]. The three interaction techniques includes visual aids to ease the perception of the 3D scene frame of reference: the axes of the 3D scene frame of reference are represented on the 3D manipulated object, thus reproducing the feedback provided in modeler software like Maya when manipulating an object. Additional aids are also provided to guide the use of the techniques, i.e. to help performing the appropriate user's input movements. For the OSP technique, fingers contact are displayed on the smartphone to visualize if they are considered joint or apart as originally designed in the Dual-Finger technique [39]. When performing rotations with ASP, a representation of the user's hand position around the smartphone is displayed as a black sphere around the manipulated object in the 3D scene. This is intended to help the user in virtually grabbing one specific vertex of the 3D manipulated object (Figure 4-center). In addition, a wireframe sphere is displayed around the 3D manipulated object: (Figure 4-center). The goal is double: to encourage the user in performing hand movements close to the smartphone and therefore better feel that the smartphone is the center of the rotations; to give the impression that when the hand is moving around the smartphone, it is also stroking the digital wireframe sphere and thus rotating the 3D object included in the sphere.

Hardware and software tracking solutions. To support the user experiment, we built a proof-of-concept prototype for WSP and ASP based on the use of an extra tool to localize the smartphone and the user's hand in 6D, as described in section 6.3. The discussion (section 9) mentions alternate embedded solutions. For the WSP technique, the position and the orientation of the smartphone are captured by the tracking system. We used quaternion representation of the orientation of the smartphone in

order to implement a relative control of the rotation movement. For the translation of the ASP technique, the position of the user dominant-hand (H_{SP}) is measured with regards to the smartphone position and orientation. Regarding the rotation performed with ASP, converting the position of H_{SP} into an orientation is a technical issue specific to this technique. Our solution relies on the use of axis-angle representation and Rodrigues formula. At each frame, we compute the 3D rotation matrix required to transform the previous H_{SP} into the current H_{SP} .

6. USER STUDY

The study includes two distinct sessions: the first (resp. second) session consisted in applying 3D translations (resp. rotations) to a 3D object. For these two sessions, the goal of this study is to evaluate and compare the performance, usability and user preference of the three techniques introduced in the previous section. We hypothesize that the around-device technique (ASP) will be more efficient than OSP and WSP because hand gestures are easier to perform, control and understand. ASP will also be preferred over the two others because it is more comfortable to use given the possibility to freely adjust the position and orientations of the smartphone.

6.1 Task and Mapping

For the two sessions, participants were instructed to perform the task as quickly and accurately as possible. For the three interactions techniques, participants start and validate each trial by pressing the same button displayed on the smartphone screen.

During the 3D translation task, we asked participants to reach a 3D spherical target in a 3D environment by translating a small 3D spherical cursor (Figure 4-left). The spherical target is always displayed in the center of a 3D cube delimiting the 3D environment. A representation of the axes is attached to the spherical cursor. In addition, stars representing the center of the spherical cursor are projected on two planes of the 3D scene contour. These visual aids are displayed in blue. The same visual aids related to the target sphere are displayed in red. These visual aids provide the user with a support to accurately move and position the object.

The initial position of the spherical cursor is situated in one of the 8 different directions (combining equal x, y and z translations) at two different distances (12.99 and 8.66 units) from the spherical target. The spherical cursor has a fixed radius of 0.5 units. We implemented two different spherical target radiuses (0.5 and 1.7 units) to produce 4 Index of Difficulties (2.6, 3.11, 4.19 and 4.75 bits). The participant can validate the 3D translation task when the cursor collides with the spherical target.

During the 3D rotation task, we asked participants to rotate a tetrahedral cursor until it fits the orientation of the tetrahedral target (Figure 4-center). The two tetrahedral centers are always located in the center of the 3D environment. Spheres of different colors are attached to the vertices of the tetrahedral form. The tetrahedral target is always displayed in green with a fixed orientation. In contrast, the tetrahedral cursor is displayed in brown. These visual aids provide the participant with indications to correctly interpret the current and targeted orientations of the 3D objects.

The initial orientation of the tetrahedral cursor is a combination of rotation axes (XY, XZ, YX, and XYZ) with one of the two angle values (50° and 100°), giving a total of 8 different starting orientations. The participant can validate the 3D orientation task when all the colored spheres of the tetrahedral cursor collide with the corresponding colored spheres of the tetrahedral target.

6.2 Design and Procedure

The 3D translation session follows a 3x4 within-participants design with Interaction Technique (ASP, WSP and OSP) and Index of Difficulty (2.6, 3.11, 4.19 and 4.75 bits) as factors. Three blocks were run for each technique, the Interaction Technique factor being counterbalanced by the use of a 3x3 Latin Square. Each block of trials required 32 translations of the target: 8 different directions for each Index of Difficulty. Inside each block the 32 trials were randomly ordered. Each participant performed 3 techniques x 3 blocks x 4 ID x 8 directions = 288 trials.

The 3D rotation session follows a 3x4x2 within-participants design with Interaction Technique (ASP, WSP and OSP), Axes of Rotation (XY, XZ, YX, and XYZ) and Angle (50° and 100°) as factors. As the 3D translation session, three blocks were run for each technique, the Interaction Technique factor being counterbalanced by the use of a 3x3 Latin Square. Each block of trials required 16 rotation of the target: 4 axes of rotation x 2 angle x 2 iterations. Inside each block the 16 trials were randomly ordered. Each participant performed 3 techniques x 3 blocks x 4 axes of rotation x 2 angle x 2 repetitions = 144 trials.

All the participants first perform the 3D translation session followed by a break and the 3D rotation session. They finish with a questionnaire session. Before using a technique for the first time participants perform a training session that consists in 32 translations of the target for 3D translation session and 16 rotations of the target for 3D rotation session. On average, all the experiment lasted 124 minutes.

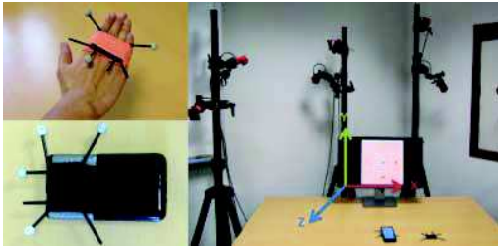


Figure 5. Experimental setting.

6.3 Participants, Apparatus, Collected Data

We recruited 12 participants (4 female) aged 28 years on average (SD=6.9). None had previously played 3D games on smartphone. Nine had used gestural interaction (Wiimote or Kinect).

Our setting is composed of a distant display, a smartphone and motion capture for tracking the smartphone and the user's hand (Figure 5). The distant display used is a 24" monitor with a resolution of 1920x1080px. To implement all 3D content, we used the Irrlicht C++ open source engine based on OpenGL. The resolution of the 3D content is a square of 1000px and the 3D environment run at 300fps. For the smartphone, we used a Samsung Galaxy S2 smartphone (6.6x12.5x0.8cm, 116 gr., 4.3" screen) running Android 4.1.2. The motion capture is based on infrared optical markers tracked by 8 OptiTrack cameras (1mm precision, 100fps). One marker is attached to the back of the smartphone using Velcro touch fastener. The second marker is fixed to the hand participant with a self-adhering bandage.

We logged all tracking data and measured completion time from stimulus onset. We asked participants to rank the three techniques according to their preference after the 3D translation session, after the 3D rotation session and once again after having achieved rotations and translations. We also measured the usability of each technique via the System Usability Scale questionnaire (SUS) [4]

and their attractiveness via the AttrakDiff questionnaire [3] AttrakDiff informs on the attractiveness of a technique according to three distinct dimensions: the pragmatic quality (PQ) indicates whether the user can achieve his goals; the hedonic quality (HQ) indicates to what extent the technique enhances the possibilities of the user; the attractiveness (ATT) expresses how the user values each technique based on its quality and engagement.

7. RESULTS

7.1 3D Translation

Task completion time data do not follow a normal distribution (Shapiro-Wilk test, $p < 0.001$). We did not find any data transformation that would allow us to use parametric tests. Our statistical analysis is thus based on non-parametric tests.

Figure 6-a summarizes the task completion times for each technique: "Around the SmartPhone" (ASP), "On the SmartPhone" (OSP) and "With the SmartPhone" (WSP). A Friedman test reveals a significant effect of the Interaction Technique factor on task completion times ($\chi^2(2)=18.17$, $p < 0.001$). A post-hoc test using Wilcoxon with Bonferroni correction establishes a significant difference between ASP (2.54s) and OSP (6.87s) ($p < 0.001$) and between WSP (2.43s) and OSP ($p < 0.001$). No significant difference exists between ASP and WSP.

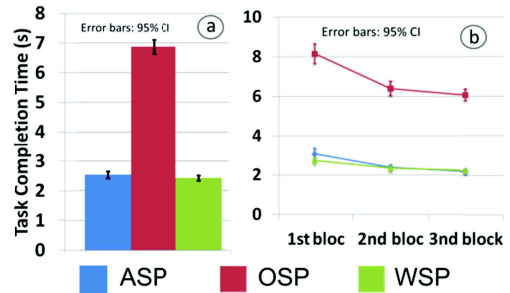


Figure 6. Task completion time (a) and learning effect (b) for 3D translation.

Friedman tests reveal a significant effect of the **block order** on task completion time for WSP and OSP techniques (WSP: $\chi^2(2)=7.82$, $p=0.02$; OSP: $\chi^2(2)=12.18$, $p=0.002$). A post-hoc test using Wilcoxon with Bonferroni correction shows a significant difference between the first and the last block for WSP and OSP techniques (Figure 6-c). Completion time is reduced of 18.5% (0.5s) for WSP ($p < 0.001$) and 34.6% (2s) for OSP ($p < 0.001$). These results confirm the difficulty to learn gestures required with the OSP technique. Concerning the WSP technique, the learning effect may be explained by the need to find an appropriate way of handling the smartphone during the first trials. Regarding the ASP technique, although the reduction of the completion time is close to the one observed with OSP technique (ASP: 28.6%, 0.9s), the difference is not significant ($p=0.08$).

After performing the translations only, 8 participants rated WSP technique as the **preferred technique** and 4 the ASP technique. In contrast, all the participants ranked OSP technique in last position. For the statistical analysis, we gave a score of 1 to the most preferred technique and a score of 3 to the least preferred technique. A Friedman test reveals a significant effect of the interaction technique on the score representing the user preference ($\chi^2(2)=18.67$, $p < 0.001$). A post-hoc test using Wilcoxon with Bonferroni correction shows a significant difference between ASP (1.67) and OSP (3.0, $p=0.005$) and between WSP (1.33) and OSP ($p=0.005$): ASP and WSP techniques are preferred to the OSP technique when performing translations.

7.2 3D Rotation

Task completion time data does not follow a normal distribution (Shapiro-Wilk test: $p < 0.001$). Our statistical analysis is thus based on non-parametric tests.

Figure 7-a summarizes the task completion time for each technique. A Friedman test reveals a significant effect of the Interaction Technique on task completion time ($\chi^2(2)=10.67$, $p=0.005$). A post-hoc test using Wilcoxon with Bonferroni correction establishes significant differences ($p < 0.001$) between each technique: OSP (8.43s), ASP (6.81s), WSP (5.40s). The discussion section further refines these results.

These results remain similar and significant when considering the different values of the Angle factor independently. However, we did not observe any significant effect of the Axes of Rotation factor on task completion times for each Interaction Technique (ASP: $\chi^2(3)=1.9$, $p=0.593$; WSP: $\chi^2(3)=5.5$, $p=0.138$; OSP: $\chi^2(3)=6.3$, $p=0.098$).

Friedman tests reveal a significant effect of the **block order** on task completion time for WSP technique only ($\chi^2(2)=12.17$, $p=0.002$). A post-hoc test using Wilcoxon with Bonferroni correction shows a significant difference between the first and the last block for this technique (Figure 7-b): completion time is reduced of 28.8% (1.4s) for WSP ($p=0.006$). As in the translation session, this learning effect may be explained by the need to find an appropriate way for handling the device in the first trials. Although the task completion time reduction with ASP (28.6%, 1.7s) is comparable to the one measured for the WSP technique, the learning effect is not statistically significant for this technique. Interestingly, the reduction of completion time with OSP between the first and third block is limited to 13.3% (1s). This improvement is below the one observed with the other technique: it is probably due to the fact that the gestures required in OSP for triggering the rotations are similar to those required to perform the translations and the rotation session always came after the translation session. Participants were thus used to the technique.

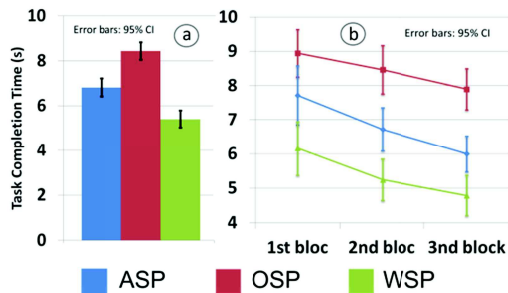


Figure 7. Task completion time (a) and learning effect (b) for the 3D rotation.

Following the rotation session, 7 participants rated ASP technique as the **preferred technique** and 5 the WSP technique. In contrast, 9 participants ranked OSP technique in the last position. For the statistical analysis, the same scoring was applied than in the translation session. A Friedman test reveals a significant effect of the interaction technique on this score representing the user preference ($\chi^2(2)=10.17$, $p=0.006$). A post-hoc test using Wilcoxon with Bonferroni correction reveals a significant difference between ASP (1.58) and OSP (2.75, $p=0.033$) and between WSP (1.67) and OSP ($p=0.017$). ASP and WSP technique are preferred to OSP when performing rotations.

7.3 Overall Task Results

Given that combining 3D translations and 3D rotations affects performances [26], these two tasks were separated in our user study. However, as tools supporting both of them, we asked the participants to evaluate the three techniques in terms of usability, attractiveness and user preference.

A **SUS score** was computed for each technique [4]: given this score the usability of the WSP technique is rated “excellent” (89.17, $SD=9.73$), the ASP technique is “good” (76.67, $SD=16.11$) and the OSP technique is “ok” (51.04, $SD=17.04$). A Friedman test reveals a significant effect of the interaction techniques on the SUS score ($\chi^2(2)=14.6$, $p < 0.001$). A post-hoc test using Wilcoxon with Bonferroni correction shows a significant difference between ASP and OSP scores ($p=0.009$) and between WSP and OSP scores ($p < 0.001$).

To measure the **attractiveness** of the three techniques we relied on the Attrakdiff method [3]. We summarize in Figure 8, the results of the Pragmatic Quality (PQ) and Hedonic Quality (HQ) dimensions. According to the Attrakdiff report, ASP technique is rated as “rather desired”. With regards to PQ and HQ dimensions, the Attrakdiff report concludes there is room of improvement in terms of usability but the technique is very hedonic: the user identifies with the technique, which motivates and stimulates him. WSP technique is rated “practice oriented”: the technique assists the user optimally but there is room of user’s stimulation improvement. Finally the OSP technique is rated “neutral”: there is room for improvement in terms of usability and user’s stimulation.

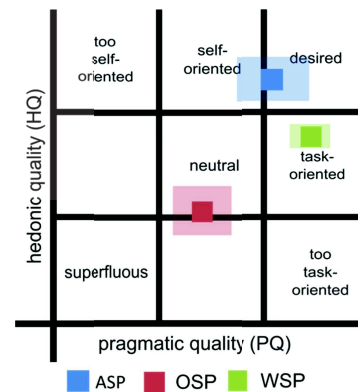


Figure 8. Portfolio generated using the AttrakDiff method.

In addition the overall user’s impression (Attractiveness ATT) of ASP (ATT=2) and WSP (ATT=1.5) techniques is considered very attractive. For the OSP technique the overall impression is moderately attractive (ATT=-0.8).

When considering the overall 3D manipulation task, 7 participants rated ASP technique as the **preferred technique** and 5 the WSP technique. In contrast, 10 participants ranked OSP technique in the last position. When applying the scoring process previously described, difference between these three results appear to be statistically significant. They are also coherent with those obtained in the translation and rotation sessions.

Globally, users expressed that the ASP technique is funny, accurate and original. But they noticed that it requires a little time of adaptation and it is a two-handed interaction technique. The WSP technique is considered easy to understand and intuitive but tiring due to the weight of the smartphone. In addition they mentioned that it needs many twisting of the wrist. Finally, participants stated that the OSP technique is convenient to use.

But they underlined the lack of accuracy and difficulty for combining the use of two fingers, especially during 3D translations.

8. COMPLEMENTARY USER STUDY: ENHANCING FEEDBACK VISIBILITY

The main difference between the two best performing techniques (ASP and WSP) is that ASP allows a permanent access to the feedback provided on the smartphone screen, while many manipulations of WSP results in turning the smartphone screen away from the user's eye. If annotations or pictures for example were displayed on the smartphone screen, WSP would have to be modified to allow a permanent access to this visual feedback. More clutching would thus be required than in the current version of WSP, thus affecting its performance.

To evaluate the impact of such constraints on the performance measured in the first study, we performed a complementary study focusing on the rotations task only. For this user's study we introduced two revised versions of WSP that constrained the user to apply small rotations only to the smartphone: it ensures that eye-access to the smartphone screen is always possible.

The goal of this complementary study is to compare the two newly introduced techniques called WSP_45 and WSP_70, with which rotation angles applied to the smartphone were respectively measured up to 45° and 70°, to WSP_WC in which rotation angles applied to the smartphone were measured without constraint as in the WSP technique used in the first user study.

8.1 Experimental settings

Tasks and mapping. Only the 3D rotation task session performed in the first experiment was proposed to the user in this second user's study (see section 6.1).

Design and procedure. The rotation task to achieve was the same as in the first study. The study followed a 3 (IT) x 4 (rotation axis: XY, XZ, YX, XYZ) x 2 (angles: small, large) within-participants design as the first study, except that interaction techniques considered here are WSP_45, WSP_70 and WSP_WC. Techniques were counterbalanced over the 6 participants. For each technique, participants performed one block as defined in the first study. A training session included one block with WSP_WC first and one with WSP_45.

Participants, Apparatus, Collected Data. We randomly recruited 6 participants among the 12 involved in the first study. The same apparatus than in the first experiment is used (see section 6.3). We logged all tracking data and measured completion time from stimulus onset.

8.2 Results

A Friedman test reveals a significant effect of the technique on task completion times ($\chi^2(2)=6.33$, $p=0.042$). A post-hoc test using Wilcoxon with Bonferroni correction establishes a significant difference between WSP_45 (4.53s) and WSP_WC (3.16s) ($p=0.001$) and between WSP_45 (4.53s) and WSP_70 (3.40s, $p=0.043$). No significant difference exists between WSP_70 and WSP_WC. As hypothesized, limiting the rotations angles increases clutching and reduces the performance.

Focusing on the 6 participants involved in the complementary study only, no significant difference exists in terms of completion time between WSP (first study, 3.19s) and WSP_WC (3.16s, Wilcoxon test: $p=1.00$). This allows us to compare the results of this study with other results of the first study.

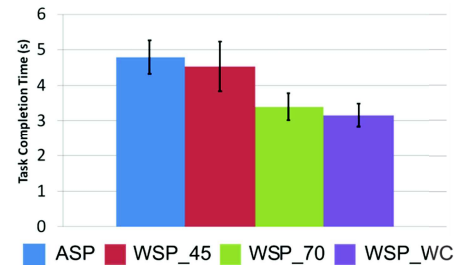


Figure 9. Task completion time for the 3D rotation with ASP and the three different WSP techniques.

When comparing the new WSP versions to ASP (Figure 9), a Friedman test reveals a significant effect of the interaction technique (ASP, WSP_WC, WSP_70, WSP_45) on task completion time ($\chi^2(3)=12.6$, $p\text{-value}=0.006$). In addition to the results of the first study, a post-hoc test using Wilcoxon with Bonferroni correction still establishes a significant difference between WSP_70 (3.40s) and ASP technique (4.80s, $p<0.01$): but combined rotations of 70° around 2 or 3 axes may result in situations where the smartphone screen is no longer readable.

Very interestingly, no significant difference exists between WSP_45 and ASP ($p=0.47$): they both perform similarly for applying rotations with a distant 3D display and are both compliant with a permanent eye access to the smartphone screen.

9. DISCUSSION

Our study reveals that the OSP technique, i.e. one of the best tactile interaction techniques available in the literature, is worse than ASP and WSP, since the first trial, in terms of **user's performance** when achieving a 3D manipulation task on a distant screen displaying the 3D scene. Performances of the tactile (OSP), tangible (WSP) and around-device (ASP) techniques are equally sensible to the difficulty of the task (angle, number of rotation axis, target size and distance). Unlike our initial assumption, in our studies users do not perform better with ASP than WSP: no significant difference has been observed for 3D translation and 3D rotations when the smartphone-screen must remain visible to the users. Without this constraint, the tangible technique (WSP) performs significantly better the 3D rotations only, but obviously does not any more support the possibility to visualize additional feedback on the smartphone since the screen may be hidden.

In terms of **usability, attractiveness and user preference**, OSP is far below ASP and WSP. Focusing on ASP and WSP, their usability score is similar and high ($SUS > 75$). ASP is preferred over WSP and was evaluated more attractive and desired than WSP. All these results are statistically significant. Different reasons can explain these results. Indeed, with the WSP technique the phone is moved in the air during the tasks: its weight may be a first cause for reducing the attractiveness of this technique. Furthermore, rotating the wrist is cumbersome: participants may be afraid of dropping the smartphone. As opposed to WSP, ASP is based on the motion of an empty hand around the device: it is safer, lighter and easier, thus preferred.

We now analyze the results related to the characteristics that have driven the design of ASP (cf. Table 1). In terms of **input frame of reference**, using the coordinate system of the displayed environment (i.e. world reference) as the reference for user input is the most common approach in VR. Furthermore, mismatches between the input and 3D scene frames of reference affect the performance [42] partly because people typically lack experience with rotation about an axis that has an arbitrary spatial

relationship to the object [33]. Although the input frames of reference of WSP and ASP are respectively world reference and the smartphone, we did not observe in these studies significant difference between the users' performance with WSP and ASP. We believe that the design of ASP provides an original and appropriate solution to cope with such frame of reference mismatch issues because the smartphone can be seen as a physical landmark. This landmark contributes to overcome the arbitrary relationship between the two frames of reference because it reifies the coordinate system in which gestures has to be performed to move an object in 6DOF. This hypothesis is in line with previous work related to bimanual interaction [12]. Future works are required to precisely establish under which conditions an around-device technique provides a better support for interacting with a distantly rendered 3D scene, and especially for situations involving predefined and high mismatches of frames of reference, similar to those involved in Ware's experiment [42].

DOF combination and input space were more limited in OSP than in ASP and WSP. We believe that this is partly responsible for the low OSP performance results. The **visibility of the feedback** provided by the smartphone was not concretely evaluated in our study, since no dynamic information relevant to the task was provided to users. However, the complementary user study clearly established the effect of this characteristic on the performances.

Finally, one limitation of our study is the detection mechanisms of the hand and smartphone motions in the WSP and ASP techniques: the technology used in this study is external to the smartphone and will very unlikely be available in many places. But, this solution was used to ensure robust and accurate measures to support the evaluation of the technique. Thinking in terms of a proof-of-Concept version of the technique might however rely on many existing solutions: proximity sensors on some Samsung devices already allow page browsing based on hand-motions detection; camera resolution are always increasing on current smartphone; small depth camera sensor [21] also constitute an alternative.

Social acceptability issue is a second limitation of around-device techniques. Would a user accept to move his/her hand around the smartphone to interact with a distant display in an office or public context? Recent works started to explore this acceptability question [35] and we will explore it through in-situ evaluation.

10. CONCLUSION AND FUTURE WORK

In this paper, we presented the first around-device interaction technique ("Around the SmartPhone" - ASP), based on a smartphone and used to manipulate 3D elements displayed on a distant screen. The design was guided by reasoning on four characteristics discriminating existing smartphone-based tactile and tangible interaction techniques with 3DVE.

To evaluate this new interaction technique, we performed two controlled user studies to compare ASP to a tangible ("With the SmartPhone" - WSP) and a tactile ("On the SmartPhone" - OSP) smartphone-based techniques taken from the literature. These evaluations reveal that WSP and ASP perform better than OSP in 3D translation and rotation. WSP and ASP perform similarly in 3D translation. They also perform similarly in 3D rotation when eye-access to the smartphone-screen is maintained all along the task. Otherwise, WSP is significantly faster than ASP but does no longer support an access to additional feedback provided on the smartphone screen.

From a qualitative point of view, ASP is the most attractive and preferred technique. It also minimizes the risk of dropping the smartphone and physically materializes the input frame of reference.

This work confirms that an "around the smartphone" interaction technique to control distant 3D is a very good alternative to tactile and tangible solutions: this is in line with results observed when interacting with 3D scenes directly displayed on the smartphone. We also revealed the need to further explore the impact of the smartphone, considered as a physical handled landmark, on the user's ability to cope with mismatch between input and 3D scene frames of reference. In the future, we plan to integrate ASP and WSP techniques in a concrete public scenario in order to observe limitations inherent to an in-situ context and to explore further optimizations of ASP and WSP, such as in [1, 40], in order to reduce the need for clutching.

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