Evaluating Object Manipulation Interaction Techniques in Mixed Reality: Tangible User Interfaces and Gesture

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ABSTRACT

Tangible user interfaces (TUIs) have been widely studied in computer, virtual reality and augmented reality systems and are known to improve user experience in these mediums. However, there have been few evaluations of TUIs in wearable mixed reality (MR). In this study, we present the results from a comparative study evaluating three object manipulation techniques in wearable MR: (1) Space-multiplexed identical-formed TUI (i.e., a physical cube that acted as a dynamic tangible proxy with identical real and virtual forms); (2) Time-multiplexed TUI (i.e., a tangible controller that was used to manipulate virtual content); (3) Hand gesture (i.e., reaching, pinching and moving the hand to manipulate virtual content). The interaction techniques were compared with a user study with 42 participants. Results revealed that the tangible cube and the controller interaction methods were comparative to each other while both being superior to the hand gesture interaction method in terms of user experience, performance, and presence. We also present suggestions for interaction design for MR based on our findings.

Keywords: Mixed reality, augmented reality, tangible user interfaces, object manipulation, user experience, evaluation.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 INTRODUCTION

In recent years, several advancements have been made in interactive technologies spanning virtual reality (VR), augmented reality (AR) and mixed reality (MR). As these are still evolving technologies with several aspects (e.g., external vs. wearable displays), there is no universally agreed concrete boundary distinctions in the literature between AR and MR yet. However, several recent studies differentiated these two mediums as AR providing overlays on the physical world that are not responsive to the physical world (i.e., a 2D information display or a 3D object that doesn't conform to the boundaries of the physical world) while MR providing digital items that are part of the physical world [12, 18, 19, 36, 50, 62], and for the purpose of this paper we adopt this perspective. In MR, digital items are placed in the physical world as if they were there, not as overlays only. They react to the physical environment and conform to the boundaries (e.g., a virtual object that is released in air doesn't pass through a physical surface in MR, but rests on it). This responsiveness is achieved through spatial mapping [53]. MR promises a more immersive experience by blending virtual projections onto real world surroundings more, to enhance the subjective reality of the user [51].

Although the aim is for the users to perceive the virtual content as part of their real-world surroundings, when they reach out to them and don't feel anything physical in air, the illusion of the reality of these virtual objects may be broken. Tangible user interfaces (TUIs) of matching forms and sizes can be promising in increasing the tangibility of the digital experience in MR and helping users perceive that they are physically feeling the virtual content. Currently, there are three widely known off-the-shelf MR headsets: Magic Leap One [47] that includes controller interaction, and Microsoft HoloLens [49] and Meta 2 [48] that both include hand gesture interaction.

Tangible interaction refers to interactions that exploit tangibility and embodiment [27]. In tangible interaction, physical artifacts that are called TUIs constitute the core of the interaction [29]. TUIs couple physical (e.g., tangible objects that can be spatially manipulated) and digital (e.g., virtual objects) representations [65]. TUIs can be divided into two: space and time multiplexed [16, 17]. Time multiplexing includes input peripherals that hold little representational significance to the virtual content in form and position (e.g., controller). Although they do not provide fully embodied interaction, controllers still serve as graspable TUI peripherals. The user can grab a virtual object by reaching out with the controller and pressing a button, then directly manipulate the object in synchrony with their hand movements. Space multiplexing refers to distributing the input and output over space, such that different virtual objects or functions have different dedicated tangible interfaces. Space multiplexing includes closely coupled interfaces in terms of virtual and physical artifacts. Space multiplexing was found to be more effective than time multiplexing in computer-based systems [15]. Since tangible interaction exploits users' innate real-world knowledge and skills through tightly coupled physical and virtual elements, it has been well explored in several digital mediums, including computer and VR systems [1, 8, 30, 32, 34, 44, 58, 70], and AR systems [2, 56].

TUIs are thought as a bridge between the virtual and physical world as they represent digital information directly and usually serve as both input and output devices. This directly aligns with the main motivation behind MR, which is to augment user's reality through blended virtual imagery. Although TUIs have been widely studied in VR and AR, there have been few studies on the space-multiplexed aspect of TUIs in MR (considering the distinction between AR and MR we adopt for this paper). Different mediums have different characteristics (e.g., display type, occlusion with physical objects etc.), which may make the applicability of the results found in one medium to the other mediums questionable.

To address this gap, in this study, we explored a space-multiplexed identical-formed TUI (cube) in wearable MR. We compared this TUI with two commonly used interactions in today's off-the-shelf MR headsets: controller and gesture. For comparison, we designed and implemented a simple object manipulation task with two modes: translation and rotation. The main contributions of our study can be summarized as: (1) Exploring the use of TUIs in wearable MR. (2) Comparing our

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TUI with the two commonly used object-manipulation interaction techniques in today's MR systems. (3) Providing insight and suggestions for future interaction designs and implementations for wearable MR, which is a relatively new medium.

2 RELATED WORK

There have been numerous forms of TUIs for different interactive mediums, such as shape displays that included form-changing tangible blocks [14], and stationary interactive surfaces and tabletop systems that included real-world props with superimposed digital imagery [3, 54, 57, 64, 66, 67]. In some early previous research, authors explored using everyday physical objects in computer and VR based interactive systems, such as using a physical doll's head for the visualization of neurosurgical operations (computer-based) [25] and picking up a physical plate while seeing its synchronous digital representation (VR-based) [26]. These tangible objects provided improved user experience in these mediums, while having the drawback of being form-specific. This encouraged the researchers to investigate more generic-formed tangible interfaces. Simone et al. compared different degrees of mismatch between physical and digital representations of objects in VR and found out that the crucial component in the shape of a TUI was the interactive part [59].

In AR, TUIs have been explored by several researchers as well. Besançon compiled the state of the art of 3D visualization interfaces that included previous works in tangible interaction in AR [2]. Sereno et al. compiled a survey of collaborative work in AR, where they mentioned tangible interaction [56].

Non-wearable AR with Stationary External Displays: Billinghurst et al. explored the augmentation of virtual content onto physical pages [4]. Ha and Woo conducted a study of 3D object manipulation methods that included simple tangible objects, such as a cup, paddle and cube, serving as controllers to interact with virtual objects [22]. Walsh et al. developed a projector-based flexible TUI system in AR, where the functionality of the tangible objects could be defined on the fly [68]. Chakraborty et al. explored interaction through a tangible cube wireframe inside which virtual anchored projections were made [6]. Gomez et al. explored a marker-based tangible interface where the user held a cube and a plane to rotate a digital brain and make selections [21]. Kruszynski and Liere explored the use of 3D-printed tangible objects as input devices for scientific manipulation [38]. Issartel et al. explored using a tangible stylus-like tool to slice volumetric datasets [31]. The study suffered from low field of view since a tablet computer was used as a display, as well as tracking issues.

Wearable AR: Kawashima et al. explored a tangible cardboard paddle for virtual object manipulation [37]. Zhou et al. developed a foldable cube, which included two-handed tangible interaction to explore the contents of a story that was digitally projected onto the surfaces of the cube [71]. Kwon et al. evaluated the effects of size and shape of tangible props on usability through tangible rectangular prisms that were coupled with various virtual objects using planar markers [39]. Tawara and Ono explored two-handed tangible interaction for medical data manipulation, where the user held a controller-like tangible item in one hand and a plane in the other hand [61]. Henderson and Feiner explored using already existing environmental features for tangible interaction [23] by superimposing 2D digital imagery onto these features (e.g., a button projection on a raised surface). Cordeil and Dwyer explored tangible interfaces for spatio-data coordination, where the user held a tangible cube in one hand and performed hand gestures on this cube (e.g., pinching) with the other hand [9].

Wearable MR: A few researchers have explored use of TUIs in wearable MR. Hettiarachchi and Wigdor developed a system that opportunistically found physical objects in a surrounding and decided which virtual object each of the physical objects would represent the best [24]. Li et al. explored combining physical and digital papers in document-intensive tasks [41].

Although not TUI focused, some researchers have explored virtual interaction in wearable MR. Piumsomboon et al. evaluated two modes of gesture-based interaction in headset-based MR on translation and rotation tasks [63]. Grasp-shell mode enabled direct manipulation of virtual objects whereas gesture-speech mode combined speech commands and gestures for indirect object manipulation. Kang et al. compared three modes of object manipulation (i.e., selection and movement): gaze and pinch, touch and grab, and worlds-in-miniature [35]. Chaconas and Hollerer evaluated bimanual hand gestures for object manipulation [5]. Xu et al. developed a hands-free interaction, which included foot movements for object selection [69].

3 INTERACTION TECHNIQUES

Three interaction techniques were implemented to manipulate a virtual cube in MR: space-multiplexed identical-formed TUI (tangible cube), time multiplexed TUI (controller), and hand gesture. All techniques afforded direct manipulation. The tangible cube and controller methods provided passive haptics while in the gesture method there was no haptics involved. The virtual cube always behaved according to the laws of Physics (when released in air, it fell under gravity and collided with physical surfaces). To maintain consistency between the three interaction modes, the projections always occluded other projections based on their depth in the user's forward direction. This way, there wasn't any difference in terms of occlusion between the combined physical and virtual cube representation (in the tangible cube mode) and the solely virtual cube representations (in the controller and gesture modes). Rigorous in-house testing was done to ensure that the implementation was interactive without any noticeable lag and as responsive to the user actions as possible within the limitations of the hardware (in tracking and field of view).

3.1 Tangible Cube Interaction

A tangible cube was custom-designed and developed for space-multiplexed embodied tangible interaction with one-to-one mapping between the physical and virtual objects (both in the form and functioning). Since the space-multiplexed aspect of identical-formed TUIs aren't well-explored in MR yet, we intentionally selected a simple object form to avoid any possible effects from the complexity of the form on the results. Hence, a cube, which is a simple object form was selected. Prior to designing the cube artifact, several tracking methods were tested on the Magic Leap system, and the most accurate way was found as the combination of controller and image tracking. Hence, the custom design of the tangible cube included a cube shell inside which the controller could be securely placed (Figure 1). The cube's size was aimed to be kept as minimum as possible to allow for one-handed interaction. Hence, the cube had edges of 11cm. It was 3D printed using PLA filament. The weight of the cube shell was 238g (390g with the controller placed inside). The cube afforded fully embodied interaction with direct manipulation. The user could hold and manipulate the cube similar to how they would do in real life. Virtual projections were made on the cube through the MR system in real time with one to one mapping (Figure 2-a). To enable accurate real time object tracking and projection mapping, a custom algorithm was used including two methods: image and controller tracking. The reason for utilizing two tracking methods was to remedy the minor lags in both methods acknowledged by Magic Leap: (1) a latency by several frames in the dynamic image tracking [45], (2) an offset in the controller tracking due to minor inaccuracies in magnetic field measurements [46]. The mentioned offset can be seen in Figure 3.

To achieve controller tracking for the tangible cube, the controller's position and orientation were tracked via the Magic Leap's software. If the speed of the controller was below a threshold (8cm/sec) and the difference between the position data from the controller tracking and image tracking was below a threshold (7cm), only the image tracking's position data was considered for calculating the virtual cube's position. Otherwise, only the controller tracking's position data was considered. The transition in switching between the two modes of tracking was made smoothly with a linear interpolation between the two positions in 0.5 seconds. For the orientation of the cube, only the controller's tracking was used since the orientation data was accurate and wasn't affected by the mentioned offsets. To reduce jittering, a smooth average damping was used (a weighted average of 30% of the previous and 70% of the current frame's position). These threshold values were decided through in-house testing.

To achieve controller tracking for the tangible cube, three images were assigned in the Magic Leap's image tracking software as the textures of the planes that were placed on the cube's opposing faces (in pairs of two, to save processing cost). Even though three pairs of two images were used, the correct orientation of the cube could always be found since image tracking was paired with controller tracking. The cube's center was calculated based on the recognized plane's position and orientation. While preparing the images, Magic Leap's image tracking guidelines were followed [45]. As the images needed to `be tracked from an arm's distance, large images were generated using a 2D fractal noise filter (Figure 1), which is a technique for generating irregular shapes [60]. The images had high contrast and a variety between the components for more accurate tracking. These images were printed out on matte photo paper (to prevent any reflection interference) and glued onto the 3D printed cube.

3.2 Controller Interaction

The controller of Magic Leap One was used as the time-multiplexed TUI. The user reached out to the virtual objects with the physical controller in hand and pulled the trigger to grab the virtual objects (Figure 4). Once the user grabbed the virtual cube, the cube was directly manipulated with one to one mapping of the hand movements using the controller's position and rotation data. The user needed to release the trigger to release the virtual cube. A gray-colored outline signifier was activated when the controller was inside the grabbable area. As they grabbed the virtual cube, the color of this shell was changed to green as a signifier. To differentiate the user experience with the two tangible interfaces in our study (i.e., the tangible cube and the controller), Fishkin's definition of embodiment can be used: while the tangible cube TUI provides full embodiment (i.e., the output device is the input device), the controller TUI provides nearby embodiment (i.e., the output is near the input object) [13].

3.3 Hand Gesture Interaction

For the hand gesture, the recommended gesture practice for controllerless MR headsets was followed (similar to the Microsoft HoloLens [49]). Hence, mid-air pinching gesture was used for object grabbing, movement and rotation. If the user pinched the virtual cube from an edge, they were able to rotate the cube in that axis by moving their hand in the pinched state. If they pinched the virtual cube from the inside, they were able to move the cube freely in three dimensions based on their hand movements (Figure 5). The translation and rotation actions were separated in the hand gesture interaction due to the limitations of the system in finger tracking caused by self-occlusion of the hand knuckles in various hand poses. The user was able to either move or rotate the virtual cube at a time with this method. Although this created inconsistency with the other two interaction methods, this was still

Figure 1: Left: The custom-designed tangible cube in its empty and assembled states. Right: The user is interacting with the cube.

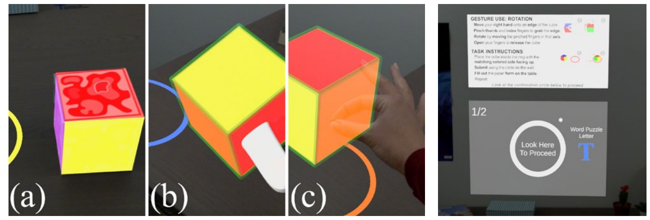

Figure 2: The user's view inside the MR headset. Left: (a) tangible cube, (b) controller, (c) gesture. Right: The virtual information display (top). The submission display (bottom).

Figure 3: The offset in projection mapping on the TUIs due to mild inaccuracies in hardware in terms of magnetic and image tracking. Left: Tangible cube. Right: Controller.

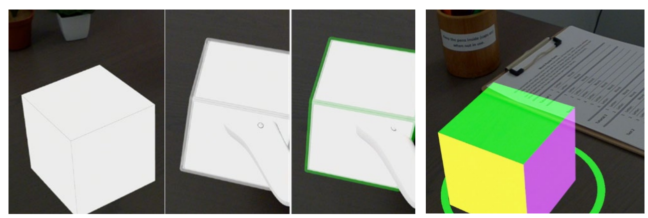

Figure 4: Controller interaction. Left: The controller was moved inside the virtual cube then the trigger was pulled for grabbing (Task 1). Right: The virtual cube was placed inside the green ring projection on the physical table (Task 2).

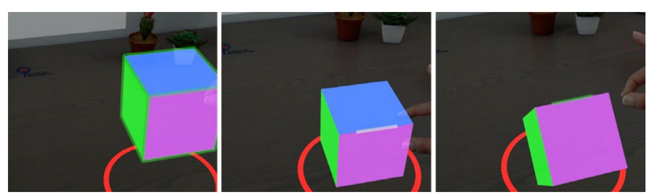

Figure 5: The user's view inside the MR headset (Task2). Left: Grabbing the cube. Middle: The hand is held near the edge of the cube (signified by the gray outline). Right: The edge is pinched, and the cube is being rotated by moving the hand (green outline).

in alignment with the best practices of the current off-the-shelf MR headsets regarding rotation gestures and the studies that utilized these headsets [5]. To remedy any possible bias due to this inconsistency with the other two methods, the tasks were also separated as translation and rotation, as described later in the paper. For finger tracking, Magic Leap's software was used. The pinched position was calculated as the middle of the thumb and the index finger (the distance needed to be smaller than 2cm for the pinching state to be activated). When in the pinched state, if the distance became greater than 5.5cm, the gesture state was switched to 'opened'. Spherical colliders were used on the virtual cube's edges for rotation (of 3cm radius) and center for translation (of 7cm radius). The virtual cube had edges of 11cm. An edge or the whole cube's outline was highlighted based on the proximity of user's hand to signify user actions.

4 EVALUATION

4.1 Task Design

To avoid from any possible bias from task complexity, simple and fundamental object manipulation tasks were designed in our study. To remedy the inconsistency between the three interaction methods in terms of rotation and to be able to separate the effects of different forms of object manipulation on user experience more granularly, two tasks were designed: translation and rotation. Similar separations in tasks were also seen in previous works [52, 55]. To provide a gradual increase in difficulty, the first level included only translation, and the second level included translation and rotation. The user's goal was to place the virtual cube inside a target ring projection (Figure 4). In the tangible cube method, the cube was represented both physically and virtually (projection overlay on the physical cube). In the controller method, the cube was represented only virtually while the controller was represented both physically and virtually (projection overlay on the physical controller). In the hand gesture method, the cube was represented virtually. In all modes, the user was able to view their hands as well as other real-life surroundings from inside the see-through MR headset. The virtual cube and ring were both projected onto a physical tabletop. To provide variety in the task, the virtual ring (of 10cm radius) was randomly placed on one of the five possible positions on the table that were equally distributed on an arc. Some real-life application areas of the designed task with the cube TUI can be: training warehouse tasks such as shelving or item sorting, education of math through cubes with different value and operator projections.

In the translation task (Task 1), the participant needed to grab the cube projection with the corresponding interaction method, move the virtual cube and place it inside the ring projection. The cube projection was solid white colored. The next position of the ring projection was randomly selected (as different than the previous one). For a correct placement, the distance between the virtual cube's center and the center of the ring on the x-z plane needed to be smaller than 7cm. In the rotation task (Task 2), different colors were rendered on each face of the cube projection, and the ring was colored as well (Figure 4). The user's goal was to place the cube inside the ring, such that the face with the matching color looked up. The colors were decided randomly from a preset pool of red, green, blue, yellow, orange, and purple.

The Information Display: A virtual information display for tutorial (with brief text-based description and pictographs) was placed on the wall to teach the users how to use the interaction modes (Figure 2). To measure the discoverability of each interaction method, these tutorials included the minimum amount of information necessary to understand each interaction method. The users were instructed to skip the tutorial screens whenever they felt like they understood how to use an interaction mode. During the testing, a brief version of the task and interaction instructions remained on the wall in case they needed to refer.

The Writing Task: One of the strongest features of MR is the incorporation of real-world surroundings into user experience. In various settings, such as education and training, users are expected to perform virtual and real-world tasks in tandem. Hence, we also aimed to explore user experience with different interaction modes when daily life tasks were merged with MR tasks, causing a context switch. To measure the effectiveness of the interaction methods when combined with real-life tasks, a physical writing task was incorporated into the experiment. The reason behind the selection of the writing task was to have the users use their both hands in the real-world task (i.e., picking up a physical pen, opening the cap etc.) and spend some time (while trying to find a word) engaged in the real-world task without being overwhelmed (to avoid any mental effect on the MR task).

After the user had placed the cube inside the ring and submitted their response, a colored letter was presented on the submission display (Figure 2) and the user was prompted to complete the word puzzle on the physical paper (Figure 4). The user needed to pick up the physical pen with the matching color, write down the displayed letter, find a word (at least four lettered) starting with that letter and write down that word. The letters were selected among a preset pool of letters with which the greatest number of words could be generated in English [11]. The colors of the letters were also assigned randomly from the same set of six colors.

The Submission Display: To prevent unintentional actions from negatively affecting user performance, a gaze-based submission mechanism was included (Figure 2). To submit their cube placements and word-puzzle completions, the user needed to look up into the confirmation ring until it was filled up (in 1.5 sec). Their progress was also displayed as a means of tracking.

4.2 The System

The system was designed for Magic Leap One [47]. LuminOS 0.97.0 and Lumin SDK 0.21.0 tools were used. A custom-developed software included the mentioned tasks and interactions.

Physical Room Lighting: We observed that floor (indirect) lighting resulted in more vividness and less transparency of the projections than ceiling (direct) lighting. Hence, three floor lamps were used with no ceiling lamps. Another concern was the minimization of the physical shadows in the TUI conditions (tangible cube and controller), to maintain consistency between the three conditions as there were no physical objects in the gesture-based interaction. The lights were placed on the two sides and the back of the user, to provide a symmetrical indirect illumination while minimizing the intensity of the physical shadows, and to minimize the reflections on the physical images on the tangible cube TUI (for more accurate image tracking). The illumination on the tabletop was measured as 690 lux.

Virtual Lighting: Our goal was to render the virtual content with the maximum intensity to: (1) prevent the users from seeing through the projections in the tangible cube TUI method, (2) make the colors more distinguishable. Hence, ambient lighting with no shadows and unlit shaders were used. The flat shading with ambient lighting was overcome by using custom-created face-contoured textures for the virtual cubes (Figure 4). Linear color space and anti-aliasing (x4) was used in the implementation.

Physical Props: Physical objects, such as a book and a ball, were mounted on the tabletop and posters were put up on the walls (Figure 1) to increase the accuracy of the spatial recognition of the Magic Leap system and to increase the immersiveness of the environment. Foot placement markers were placed on the floor to have the participants stand at a fixed distance from the table and ensure a consistent tracking performance (from the headset to the tabletop where the virtual content rested on). With similar motivations, an adjustable stand-up desk was used in the study, and the table's height was adjusted based on each participant's eye height (such that a fixed 60cm distance was maintained).

Audio: Simple sound effects were added for the following three important events: grab, drop, and ring submission.

4.3 User Study

The user study (including the pilot and the formal stages) was performed and concluded before the COVID pandemic's emergence. An IRB approval from the University of Arizona (protocol number 1803367436) was obtained for the user study.

Hypothesis: We constructed the following hypothesis: H1: Tangible cube will yield improved user experience than the other two interaction methods.

Pilot Study: A pilot study was performed with three participants. It was revealed that the spread-out MR setup needed more cueing, as the participants kept looking at the wall and didn't look down to see the projections on the table. Hence, assistive prompts, such as "look down", were added on the information and submission displays. Another improvement was made in the gesture-based interaction, as the participants had a hard time in selecting the edges of the cube. To remedy this, the cube's center detection volume was shrunk by 10% while the volumes for the detection of the edges were enlarged by 10% (decided by in-house testing).

Formal User Study: A within-subjects user study was performed with 43 participants. Each participant completed 3 tutorial and 10 task instances for each of the translation and the rotation tasks with each of the three interaction methods (78 instances in total per participant). The order of the interaction methods was randomly decided for each participant, using balanced Latin square. The independent variable in the study was the interaction mode. The inclusion criteria for the participants included the following: age between 18-35, right handedness (for consistency), a hand span greater than 6-inch (to hold the tangible cube without any physical discomfort), no eyeglasses, no disabilities or pregnancy, English proficiency, and no or minimal prior mixed reality experience (less than one hour in total).

4.4 Procedure

The participant arrived at the laboratory. Their eye height was measured. They were asked to read and sign the consent form and fill out the demographics questionnaire. The research personnel set up the inside room. They adjusted the height of the stand-up desk as 60cm lower than the participant's measured eye height. They then asked the participant to go to the inside room and fill out the pre-experiment questionnaire. If the first interaction mode was the tangible cube, the research personnel assembled the TUI in the outside room (to prevent the participant from seeing the assembly). The participant was then asked to stand on the foot placement markers on the ground. The research personnel explained them their goal and also showed them a video on an iPad that demonstrated the two tasks of translation and rotation. The participants were informed that they shouldn't use left hand or both hands at any time. They were also instructed to complete the tasks as quickly and as accurately as possible. The personnel helped the participant to wear the Magic Leap's small computer bag and headset. Headset calibration was made by asking the participant to center a four-cornered projection in their viewpoint. If the first interaction mode was controller, the personnel secured the controller on the participant's right wrist. The session was then started. The personnel started image streaming on the iPad application, to see and record a mirrored stream of what the participant was seeing inside the headset in real time. The participant completed the tutorial and testing instances of the translation and rotation tasks with the assigned interaction method. After all instances of that interaction method was completed, the participant was asked to fill out the in-experiment user experience questionnaire for that interaction method. During this time, the participant was asked to push the headset up on their heads, to prevent any unnecessary eye strain. After completing the questionnaire, the participant completed the task instances with the second interaction method, then again filled out the user experience questionnaire. This was followed by repeating the same steps for the third interaction method. At the end, the participant also filled out a post-experiment questionnaire. One session took around one hour from start to finish.

4.5 Measures and Participants

The demographics questionnaire included questions about the name, age, gender identity and contact information. The pre-experiment questionnaire consisted of questions about the prior MR experience and current motion sickness levels. The in-experiment user experience questionnaire included several adjectives regarding the user experience with each interaction method. There were also presence-related questions, which were adopted from the Lessiter et al.'s ITC-Sense of Presence Inventory [40]. Lastly, there were cybersickness questions, which were selected from the Gianaros et al.'s motion sickness questionnaire [20] based on their relevance to MR. The final question asked the participant to enter their comments about the tested interaction method. The post-experiment questionnaire asked about the participant's ranked preference of the tested interaction methods and their feedback on the overall experience. Automated data was collected for the following: correctness of placement, colors, target and user placement positions in x, y, and z axes, and time logs for user actions (e.g., skipping the tutorial). One participant's data was discarded due to them stating that they were not able to understand how to perform the tasks despite the tutorial sessions, hence the actual sample size of the user study was 42. The participants were mostly undergraduate and graduate students who were enrolled in various majors. The age range was between 18 and 35 (M = 23.55, SD = 4.915). The gender identity distribution was 25 males and 17 females. All participants received $20 gift cards.

5 Results

5.1 Automated Data

The results of repeated measures ANOVA tests with Mauchly's Test of Sphericity and according Greenhouse-Geisser corrections are presented in Table 1. There were significant differences between the three interaction methods in all metrics although no notable differences were observed between the two tasks. Completion time refers to the time it took for the participants to submit the cube projection placement in an instance. It excludes the writing time to avoid any possible bias that might have aroused from the participants' times of thinking a word with the assigned letter. Tangible cube and controller had significantly lower completion times than the gesture method. Information time refers to the seconds it took for the participant to look at the tutorial information display at the beginning of the tutorial level (Figure 4). It gives an estimation of how long it took for the participants to understand how to use an interaction method with, hence indicates the discoverability (ease of understanding) of the interaction method. The tangible cube had the lowest information time, indicating that it was easier for the participants to understand how to use the tangible cube interaction method. Placement distance refers to the distance from the center of the target ring projection to the center of the placed cube projection (calculated considering only the position of the virtual cube projection, not the TUIs). Placement distance was statistically significantly larger in the tangible cube method than the other two interaction methods for both tasks. The participants tended to center the cube more inside the ring projection with the controller and gesture methods while placing the cube closer to them non-centered (although still keeping it inside the ring projection) with the tangible cube method. Writing time refers to the time between

Table 1: Automated data statistical test results.

			Automated Data		Mauchly's Test		ANOVA with Rep. Measures			Pairwise Comparisons		
			M	*SD*	*χ2*	*p*	*df*	*F*	*p*		*SE*	*p*
Completion Time (sec)	Task1	Tangible Cube	7.59	2.50	36.44	**1.22 x 10^{-8}**	1.25	35.36	**3.18 x 10^{-8}**	Tangible Cube - Controller	0.41	1.00
		Controller	7.67	1.72						Tangible Cube - Gesture	1.02	**1.63 x 10^{-6}**
		Gesture	13.63	6.22						Gesture - Controller	0.91	**2.25 x 10^{-7}**
	Task2	Tangible Cube	9.36	1.86	69.45	**8.31 x 10^{-16}**	1.10	92.41	**5.32 x 10^{-13}**	Tangible Cube - Controller	0.36	1.00
		Controller	9.32	1.66						Tangible Cube - Gesture	1.42	**1.55 x 10^{-11}**
		Gesture	22.99	9.08						Gesture - Controller	1.37	**4.78 x 10^{-12}**
Placement Distance (m)	Task1	Tangible Cube	0.04	0.01	15.59	**4.11 x 10^{-4}**	1.51	136.10	**7.61 x 10^{-21}**	Tangible Cube - Controller	0.00	**3.25 x 10^{-19}**
		Controller	0.01	0.00						Tangible Cube - Gesture	0.00	**3.12 x 10^{-13}**
		Gesture	0.01	0.01						Gesture - Controller	0.00	3.81 x 10^{-1}
	Task2	Tangible Cube	0.04	0.01	7.00	**3.02 x 10^{-2}**	1.72	168.44	**5.43 x 10^{-26}**	Tangible Cube - Controller	0.00	**1.89 x 10^{-20}**
		Controller	0.01	0.00						Tangible Cube - Gesture	0.00	**1.71 x 10^{-15}**
		Gesture	0.01	0.01						Gesture - Controller	0.00	3.91 x 10^{-1}
Writing Time (sec)	Task1	Tangible Cube	13.94	3.07	0.78	6.78 x 10^{-1}	2.00	3.66	**2.99 x 10^{-2}**	Tangible Cube - Controller	0.61	**3.94 x 10^{-2}**
		Controller	15.52	4.31						Tangible Cube - Gesture	0.58	1.00
		Gesture	14.29	3.40						Gesture - Controller	0.65	1.95 x 10^{-1}
	Task2	Tangible Cube	14.14	3.48	3.93	1.40 x 10^{-1}	2.00	4.63	**1.24 x 10^{-2}**	Tangible Cube - Controller	0.62	**2.40 x 10^{-2}**
		Controller	15.86	4.58						Tangible Cube - Gesture	0.51	1.00
		Gesture	14.44	3.08						Gesture - Controller	0.67	1.23 x 10^{-1}
Information Time (sec)	Tutorial1	Tangible Cube	15.35	11.73	22.72	**1.16 x 10^{-5}**	1.40	11.11	**4.50 x 10^{-4}**	Tangible Cube - Controller	4.92	**1.67 x 10^{-3}**
		Controller	33.79	29.88						Tangible Cube - Gesture	2.45	2.55 x 10^{-1}
		Gesture	19.68	12.42						Gesture - Controller	4.47	**8.92 x 10^{-3}**
	Tutorial2	Tangible Cube	5.84	2.89	5.09	7.83 x 10^{-2}	2.00	22.56	**1.56 x 10^{-8}**	Tangible Cube - Controller	1.02	**9.53 x 10^{-3}**
		Controller	9.02	6.72						Tangible Cube - Gesture	0.98	**9.47 x 10^{-9}**
		Gesture	13.17	6.78						Gesture - Controller	1.27	**6.56 x 10^{-3}**

the cube placement submission and the writing completion submission (the time it took for the participant to physically write down the letter and the four-lettered word starting with that letter). It was significantly lower in the tangible cube method than the other two methods for both tasks.

5.2 Quantitative Feedback

User Experience: The user experience questions were grouped into two, based on the correlation between them: usability and efficiency. The usability adjectives included the following: easy to learn, easy to perform, natural, intuitive, comfortable, enjoyable, satisfying, tiring, frustrating. The scores for the tiring and frustrating adjectives were reversed, as they represented undesirable user experience aspects. Efficiency adjectives included the following: suitable for the task and efficient. The overall score for each group was calculated by taking the average of the scores for these metrics. The mentioned adjectives were rated by the participants on a 7-point Likert scale.

The usability results were as follows: Tangible Cube (M = 6.31, SD = 0.754), Controller (M = 6.39, SD = 0.715), and Gesture (M = 5.05, SD = 1.186). Friedman tests were carried out to compare the difference in the results between the interaction methods (N = 42, df = 2). There was significant difference in usability ($\chi 2(2)$ = 39.488, p = 2.66 x 10^{-9}) between the three interaction methods. Post hoc analysis with Wilcoxon signed-rank tests with a Bonferroni correction (p = 0.017) resulted in significant differences between the Tangible Cube and Gesture (Z = -5.010, p = 5.46 x 10^{-7}) and Controller and Gesture (Z = -5.257, p = 1.47 x 10^{-7}). There was no significant difference between the Tangible Cube and Controller (Z = -1.020, p = 0.308).

The efficiency results were as follows for each method: Tangible Cube (M = 6.01, SD = 1.090), Controller (M = 6.29, SD = 1.111), and Gesture (M = 4.54, SD = 1.882). There was also significant difference in the efficiency results ($\chi 2(2)$ = 36.597, p = 1.13 x 10^{-8}) between the three interaction methods. Post hoc analysis with Wilcoxon with a Bonferroni correction (p = 0.017) resulted in significant differences between the Tangible Cube and Gesture (Z = -4.197, p = 2.71 x 10^{-5}) and Controller and Gesture (Z = -4.831, p = 1.36 x 10^{-6}), whereas no significant difference between the Tangible Cube and Controller (Z = -1.439, p = 0.150).

Presence: Presence questions were grouped into four, according to the instructions of the ITC-Sense of Presence Inventory. The groups included the following: (1) Naturalness, (2) Spatial Presence, (3) Being Drawn In, (4) Liveliness of Content. The questions were rated by the participants on a 7-point Likert scale. Friedman test resulted in statistically significant differences between the three interaction methods in all groups. The results including the Wilcoxon test with a Bonferroni correction (p = 0.017) are presented in Table 2. The gesture method received the lowest presence scores with a statistically significant difference from the other two interaction methods for all four groups, while the controller and tangible cube received higher scores that were compatible with no significant difference between them.

Cybersickness: The following adjectives were included in the motion sickness questionnaire: disoriented, tired/fatigued, nauseated, dizzy, having a headache, having blurred vision, having eye strain, difficulty in focusing. The questions were rated on a 7-point Likert scale for consistency. The results were interpreted based on the instructions of the motion sickness questionnaire, by taking a percentage of the score over the overall maximum possible score. The difference between each participant's score and their previous score was taken into consideration for each trial. The maximum/minimum possible difference between the two conditions was ±85.71. The results for the difference were as follows: Tangible Cube (M = -0.38, SD = 8.05), Controller (M = -0.09, SD = 2.95), and Gesture (M = 2.72, SD = 9.25). Friedman test did not result in significant difference ($\chi 2(2)$ = 5.914, p = 0.052) between the three methods. None of the three methods caused significant cybersickness in users.

Preference: The preference data included the ranking of the interaction methods from the most preferred (3) to the least (1). The participants indicated their preference after completing the overall experiment. The results were as follows: Tangible Cube (M = 2.07, SD = 0.71), Controller (M = 1.98, SD = 0.81), and Gesture (M = 1.95, SD = 0.94). Friedman test did not result in statistically significant difference ($\chi 2(2)$ = 0.333, p = 0.846).

Table 2: Presence data statistical test results (on a 7-point Likert scale).

		Presence Results		Friedman Results		Wilcoxon Results		
		M	*SD*	χ^2	*p*		*Z*	*p*
Naturalness	Controller	5.185	1.424	13.917	**9.50 x 10^{-4}**	Tangible Cube - Controller	-1.095	2.74 x 10^{-1}
	Gesture	4.393	1.568			Tangible Cube - Gesture	-1.873	**6.10 x 10^{-2}**
	Tangible Cube	4.905	1.642			Gesture - Controller	-3.955	**7.65 x 10^{-5}**
Spatial Presence	Controller	5.488	1.504	11.886	**2.62 x 10^{-3}**	Tangible Cube - Controller	-1.022	3.07 x 10^{-1}
	Gesture	4.548	1.648			Tangible Cube - Gesture	-2.189	2.86 x 10^{-2}
	Tangible Cube	5.226	1.462			Gesture - Controller	-3.577	**3.48 x 10^{-4}**
Being Drawn In	Controller	5.690	1.440	8.579	**1.37 x 10^{-2}**	Tangible Cube - Controller	-0.176	8.61 x 10^{-1}
	Gesture	5.024	1.600			Tangible Cube - Gesture	-2.563	**1.04 x 10^{-2}**
	Tangible Cube	5.738	1.270			Gesture - Controller	-2.705	**6.82 x 10^{-3}**
Liveness of Content	Controller	5.595	1.449	9.121	**1.05 x 10^{-2}**	Tangible Cube - Controller	-1.217	2.24 x 10^{-1}
	Gesture	4.881	1.837			Tangible Cube - Gesture	-1.417	1.57 x 10^{-1}
	Tangible Cube	5.310	1.569			Gesture - Controller	-3.155	**1.60 x 10^{-3}**

5.3 Qualitative Feedback

Some participants mentioned that offsets in the projection overlays degraded their experience. P2: *"When the trigger was used to hold onto a cube, it moved around a little without movement of the hand."* P22: *"The colors would lag behind the [tangible] cube slightly."* Some participants had complaints about the gesture method. P14: *"I think the experiment where you use your bare hand to touch the cube is the hardest because the movement itself is so hard to do."* P15: *"I didn't like how narrow the field of vision was, so if your eyes weren't on the cube, the cube wasn't following with the command."* P4: *"I dislike that I have to pinch inside the cube in order to move it, instead of grabbing it from the outside of the cube."* Some participants though that having projection overlays on top of physical objects made these items less believable. P17: *"The fact that I can see and hold the real life cube and know it's the real life cube makes it a lot less believable."* Some participants mentioned the inefficiency of the physical cube for rotation. P25: *"I personally think the actual cube is less efficient than the controller when it comes to check the colors of different sides of the cube."* P39: *"I liked having the hand device. It seemed like the task was easier."* Some participants found the controller less realistic than the tangible cube. P22: *"The controller feels more video-gamey than picking up the real cube."* Many participants stated their liking of the high-fidelity tangible interaction (i.e., tangible cube and the controller). P1: *"It seemed a lot more natural to move it [with the tangible cube method]."* P3: *"It [the tangible cube] felt very natural and realistic."* P37: *"It felt so much better with the real cube."* P2: *"It [the controller] was simple to use."* P37: *"I loved using the controller even more than the real cube."*

6 Discussion

Usability: The tangible cube method was superior to gesture, and was comparative to controller. Hence, our hypothesis wasn't supported by the data, although it is notable to mention that the TUI-based interaction methods (i.e., space-multiplexed tangible cube and time-multiplexed controller) performed better than the gesture-based interaction. Of course, since these two methods provided passive haptics while the gesture method didn't, this result is expected, and is in alignment with previous studies in desktop systems and VR [32, 70] and AR [2, 21, 31, 68]. The placement distance had statistically significantly more offset in the tangible cube method. At the beginning of the experiment, the participants were instructed to put the cube inside the ring. However, although they centered the cube projections with the controller and gesture, they placed the cube closer to themselves rather than centering it with the tangible cube. We think that the reasons behind this can be two-fold: (1) Slightly higher physical weight of the tangible cube may have led the participants to put it barely inside the ring without centering to avoid exerting more effort. (2) The participants may have been less aware of the interaction tool and had a better sense of depth with the tangible cube and didn't need to put as much mental effort into centering it to make sure that it was inside the ring.

The completion time was significantly higher for the gesture than the other two methods for both tasks. For the rotation task, this result was expected since translation and rotation actions were separated for this method. But for the translation task, this result was not expected since all three methods had similar direct manipulation gestures. We think that two factors might have contributed to this: (1) The increased fineness and accuracy that is required for performing a hand gesture as compared to grabbing the tangible cube itself or pulling the trigger of the controller. (2) User-induced tracking losses due to not keeping the virtual cube inside the field-of-view while turning their head.

The difference was not limited to the translation task. In the rotation task, the completion time for gesture was longer, as expected. This emphasizes the drawback of including additional controls for different motions that comes with the current hand tracking limitations in the off the shelf MR headsets. This finding is in alignment with [33], where the limitation or break down of necessary motions for a task to be performed decreased efficiency in object manipulation. There is also in alignment with [35, 63], where more embodied interaction methods outperformed less embodied ones. In the tangible cube and the controller methods, the rotation could be made simultaneously with the translation. However, in the gesture method, the degrees of freedom were separated (i.e., the user needed to perform the translation and rotation motions separately), due to not being able to accurately track hand rotation in all 3 degrees of freedom with the existing image tracking system of the hardware. In the current off the shelf MR headsets, separation of degrees of freedom is used in hand gesture interactions similarly. When designing custom interactions for MR, this should be considered, especially if completion time is an important factor.

The writing time was significantly longer for the controller as compared to the other two methods. We think that the reason was the need for the user to handle the wrist-tethered controller with their non-dominant hand while writing using their dominant hand. Creators should take into consideration whether the user would need to use real-world objects or not while in MR, and design interaction methods accordingly (e.g., prefer space-multiplexed identical-formed TUIs or gesture-based interaction over controller interaction to free the users' hands in such scenarios).

Information time was significantly shorter for the tangible cube than the other two methods, meaning that it had better discoverability. Discoverability is especially important for relatively new mediums, such as wearable MR. The intuitiveness of one-to-one interaction and decreased effort for learning the interaction method can be the underlying reasons. This should be considered while designing interactions for cognitively overwhelming MR experiences to alleviate some effort.

In summary, the tangible cube was compatible with the controller in terms of user experience while these two methods being superior to the gesture method. We were expecting the tangible cube to provide improved user experience than both the controller and the gesture methods based on the previous studies where increased similarity in form and functioning resulted in better user experience [23, 39, 41]. Some drawbacks that could have contributed to this result may be as follows: (1) Effort: The tangible cube had a mildly higher weight than the controller (390g vs. 152g), which could have caused to induce more effort on the user's end for interaction. The participants also complained about the difficulty of checking the faces of the cube with the tangible cube method, mentioning that it was more difficult to do than using the controller. The controller, in this case, acted as a proxy, hence the participants were able to rotate the cube to a higher degree with less effort. (2) Tracking inaccuracies: As demonstrated in Figure 3, there were imperfections in terms of the magnetic controller and image tracking. To alleviate the possible negative effects of these minor inaccuracies in tracking, several improvements had been made prior to the user studies through custom algorithms. However, the interaction methods still suffered from these mentioned minor inaccuracies. Looking at the participant comments, we think that they were less forgiving to such inaccuracies with the tangible cube method. We believe one reason for that can be the directness of the interaction in the tangible cube method. In the controller method, the users probably mostly looked at the cube projection and not the controller itself, which could have made the offsets in the controller texture rendering less noticeable by the participants. Another reason would be the one-to-one similarity in the form of the virtual and physical items in the tangible cube method, which may have made even a slight imperfection in mapping noticeable and caused a more negative effect on user experience. These limitations should be considered while designing interactions for the off-the-shelf MR systems. We believe that our findings are also important in emphasizing different design implications required for mediums that share the reality-virtuality continuum (e.g., MR and VR). Although it has been known that space-multiplexed identical-formed tangible interaction improved user experience in VR [7, 10, 28, 42], our findings didn't indicate any superiority over the controller in MR. An underlying reason can be that in VR, users wear obstructive headsets where they don't see their physical surroundings; whereas in MR, headsets are see-through, which may require almost perfect projection mapping for believability.

Presence: There were significant differences between the three methods in all sub-categories of presence. Tangible cube and controller yielded increased presence as compared to the gesture, mostly with no significant differences within them. We think that the main underlying reason was the breaks in presence caused by the mild inaccuracies in tracking. Considering the user comments, it may have been more noticeable and disturbing for the users when there was a one-to-one mapping of the projections onto the tangible object, causing a decrease in presence. We believe that the reason for the low presence scores for the gesture method was the losses in tracking due to the users' head rotations that caused the grabbed virtual cube to drop due to being out of their field of view. Both TUIs (i.e., tangible cube and controller) increased presence as compared to the in-air gestures, in alignment with the previous work [43]. Another possible factor can be related to the perception of virtual content. Some participants mentioned that it was less convincing for them to see projections that were mapped one-to-one onto a real-life object (i.e., the tangible cube), which they could physically see and know that it was there, as part of their real-world surroundings, as compared to seeing separate and independent virtual objects with no tangible counterparts. In MR, in-air virtual projections that are not mapped onto physical objects may appeal more to users and be more likely to be perceived as desirable augmentations than one-to-one mappings onto real-world objects. Within the presence questionnaire, the participants were asked to rate how much they wanted to touch the virtual content. Although there was no significant difference, they gave high scores to all of the three methods. This interest for touching the projections can be exploited when designing MR experiences.

Preference: There were no significant difference in preference scores between the three methods. This is not in alignment with [39], which was conducted in wearable AR. The interaction in [39] was simpler than our study, which may explain the difference (the user was required to touch and slide the overlaid planar projections, not manipulate in 3D). This result is also not in alignment with [41], which was conducted in wearable MR. Similarly, in [41], users were required to read information on virtual vs. physical papers and not manipulate in 3D. We think that this indicates that more studies are needed to evaluate user preference in wearable MR with varying degrees of manipulation-oriented tasks. We also link the indifference in preference in our study to the recentness of the technology. We think that since for most of the participants it was their first MR experience, they might not have been very specific in their preference of interaction method, and might have been more open.

Scalability of TUIs: We explored simple-formed TUIs in this study as a starting point to understand the use of TUIs in MR. In the scalability of TUIs there may be limitations on some object properties, such as weight and size. Heavy objects can degrade user experience in dynamic scenarios in MR as it would require more effort. Large objects can block the already small-sized field of view to a high degree and degrade user experience. TUIs can be especially valuable in expanding the physical objects in terms of content (e.g., several textures can be projected onto the same physical object to give the illusion of different items). However, it should be noted that in our study, user experience with the identical-formed TUI (cube) suffered more from the imperfections in projection caused by the minor tracking inaccuracies.

Limitations: In this study, we focused on a dynamic task where the users needed to both move and rotate virtual objects as well as their heads. Our results are task dependent. Minor inaccuracies of the current off-the-shelf MR hardware in tracking should also be considered while interpreting the implications.

7 Conclusion and Future Work

In this study, we evaluated three object manipulation techniques in wearable MR: (1) Space-multiplexed identical-formed TUI (tangible cube); (2) Time-multiplexed TUI (controller); (3) Hand gesture. For comparison, two object manipulation tasks were used: translation and rotation. An additional real-world task (writing) was also included to measure the effects of the interaction methods on context switching. The controller and the tangible cube were superior to the gesture method, while being comparable to each other in terms of user experience. User experience with the controller suffered from task context switching while the tangible cube suffered from increased awareness of the participants of the imperfections in the alignment of projections. Our study can be useful in guiding the design and implementation of future tangible interfaces for MR. Since the two TUI interaction methods (tangible cube and controller) were superior to the gesture method, it is justifiable to explore further directions in the use of TUIs in MR. TUIs with more complex forms or higher weights can be explored in the future.

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