Usability of Hybrid, Physical and Virtual Objects for Basic Manipulation Tasks in Virtual Environments

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ABSTRACT

Integrating physical and virtual environments has been shown to improve usability of Virtual Reality (VR) applications. Objects within these mixed realities (MR [1]) can be hybrid physical/virtual objects that are physically manipulatable and have flexible shape and texture.

We compare usability of hybrid objects for basic manipulation tasks (rotation, positioning) to physical and virtual objects. The results suggest that hybrid objects are manipulated faster than virtual objects, but not more accurately. Physical objects outperform both hybrid and virtual objects in terms of speed and accuracy. On the other hand, users felt most stimulated by the virtual objects, followed by the hybrid and physical objects.

The study shows that hybrid objects "work" in virtual environments, but further investigations regarding the factors influencing their usability are needed.

CR Categories: H.5.2 [User Interfaces]: Input devices and strategies; I.3.6 [Computer Graphics]: Methodology and Techniques – interaction techniques.

Keywords: Hybrid Objects, VR Interaction Techniques, Tangible Virtual Environments, Props, Tangible User Interfaces, Canonical Manipulation Tasks, Virtual Reality, Mixed Reality

1 INTRODUCTION

Interacting with digital objects, especially grasping and physically manipulating by the user, is still an issue in (semi) immersive virtual environments. This is due to technological limits of available Virtual Reality (VR) interaction techniques and devices, e.g. exoskeletons and force-feedback-arms, which are either too coarse, too inert or provide solely pointwise scanning of an object's surface. It remains uncertain if devices will ever be capable of creating the illusion of touching, holding, grasping and manipulating digital objects. From a sensomotor perspective complex physical interactions like leafing through a book, playing cards, or sorting objects of various shapes and sizes are hard to translate into virtual environments. As a solution, many current VR systems use gestural or verbal commands for the control of objects (e.g. put-that-there interaction technique), which are harder to automate by the user and thus require more cognitive resources [2].

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IEEE Symposium on 3D User Interfaces 2007
March 10 - 11, Charlotte, North Carolina, USA
1-4244-0907-1/07/$25.00 ©2007 IEEE

In terms of basal characteristics, the advantages of physical objects can be seen in their tangibility, which allows application of long-trained and automated manipulation skills by the user, their rich physical properties, which facilitate communication of physical affordances to the user, and the optimum integration of action and perception space which accelerates manipulation speed and accuracy [3, 4]. Digital objects, especially graphically represented virtual objects, are highly flexible in terms of shape and visual texture (intrinsic properties), and position and orientation (extrinsic properties). Because standardised graphical libraries are available (e.g. OpenGL), virtual objects are easily programmable, in contrast to physical artefacts.

Hybrid objects in virtual environments which consist of seamlessly aligned physical and virtual parts could provide a means to combine advantages of both virtual and real objects. In an effort to find some generalizable evidence about the usability of hybrid objects, we decided to investigate performance in accomplishing the *canonical manipulation tasks (CMT*) *positioning* and *rotating* which are, from a very simplified point of view, said to be the building blocks for complex interaction scenarios [5]. Due to the very different strategies for acquisition of virtual and physical objects and in order to keep the conditions comparable, we left the study of the CMT *selection* for further studies. We consider selection as an artificial, machine inflicted interaction token. "Natural" interaction with physical objects knows mental but no physical selection, grasping movements are not single interactions but always anticipate the planned manipulation, e.g. by moving the wrist accordingly. Humans perceive grasping and manipulating as entwined chunks [6], but today's VR (and also GUI) interaction techniques strictly separate selection and manipulation of objects.

2 PREVIOUS WORK

Because the useful characteristics of physical and virtual objects are complementary to a certain extent, several elaborated approaches exist to incorporate virtual and real environments , e.g. Ubiquitous Computing, Tangible Interaction, Augmented Reality, Mixed Reality. Milgram and Kishino describe the extent to which real and virtual environments can be mixed (Mixed Reality, MR) in terms of the virtuality continuum, from real environments through Augmented Reality (AR) and Augmented Virtuality (AV) to virtual environments [1]. In contrast to Augmented AR, which inaugurates virtual objects in real environments, our work focuses on AV by integrating real objects, e.g. props [7, 8] or tangible interfaces [9, 10] into tangible virtual environments. Here we investigate the usability of hybrid objects in virtual environments for basic manipulation tasks.

Lok et al. [11] proposed hybrid environments (HE) in order to enable natural interaction and enhance their effectiveness. In their approach, computer generated hulls of physical objects are being integrated into the virtual scene. The user manipulates the real objects and simultaneously its virtual counterpart. Several case studies showed that HEs, compared to standard VEs, reduce training time, improve recognition of known objects, are more familiar to the users and provide physical motion constraints, e.g. for screw threads and outlet plugs.

Zhai et al. [12] compared the performance of a 6 degree-of-freedom (DOF) data glove which allows only the use of large muscle groups (arm and shoulder) with an 6 DOF FingerBall, which can also be controlled with fine, smaller muscle groups and joints in the fingers. They found that in a docking task, users were significantly faster with the FingerBall than with the glove. This results suggest that hybrid environments in which many of the interactive objects are controllable with fingers outperform conventional, glove based virtual environments when fine motor skills are required.

Kitamura et al. [13] investigated the effect of physical laws in hybrid environments, here magnetism. Their case only had visual feedback and no force feedback. They showed that user performance in manipulation task is improved if virtual and real objects respond in a similar manner to the same physical laws.

Ware and Ross [4] compared rotation of objects with real and virtual visual feedback. In one study, all objects were manipulatable by wooden controls of the same size and shape. In the virtual condition, the objects were projected in the same space as the hands, using a mirror which blocked the view onto the real handles and subjects' hands. The rotation of virtual objects in their study took 2.25 seconds - significantly longer (450ms) than the rotation of real objects, which took 1.80 seconds. They suggest that the main factor in the difference between real objects and virtual objects was lag introduced by the use of computer graphics and hand tracking apparatus. In another study, they found that it took subjects significantly less time to rotate objects with the controller object in the same spatial location as the virtual object being rotated (3.70 seconds) than with a 60 cm displacement between hands and rotated virtual object (4.96 seconds).

Most of the studies compared entirely physical and virtual objects. The objective of our study was to investigate usability of hybrid objects for basic manipulation tasks in comparison to virtual and physical objects.

3 Hybrid Objects in Virtual Environments

Hybrid objects in virtual environments consist of seamlessly aligned physical and virtual parts. They can be physically manipulated with their physical part and gain dynamic flexibility through their graphical extension. Hybrid objects could find applications in a large number of domains where tangibility and flexibility are crucial, e.g. product development or management of information spaces.

Beside implementation errors (e.g. calibration errors or interpupillary distance mismatches) and current technological limitations (system update rate, restricted field of view, mismatches of resolution and image clarity, luminance and contrast, and viewpoint dependency), Drascic and Milgram [14] list several unresolved problems for aligning real and virtual objects, which relate to perceptual issues and influences usability of hybrid objects:

Occlusion is the strongest cue for the perception of object's depth and spatial relationships, in that it can override all other cues. Rendering the occlusion of virtual and real objects is an ongoing research issue. In our scenario with back projection, physical object parts will always occlude virtual parts.

Expanded Depth of Field: stereoscopic displays have an "infinite" or greatly expanded depth of field, which might lead to distraction and interference.

Absence of accommodation: with known technology, the imaging plane is always closer to the viewer than the objects would be.

Accommodation - vergence conflict: In stereoscopic displays, viewer's eyes have to accommodate (focus) at the depth of the display which is in conflict to the rotation movement of both eyes in opposite directions when following an object (convergence). This is why viewers see virtual objects at a distance closer to the screen than convergence might suggest.

Accommodation mismatch: the accommodation distance for the real object corresponds with the position of the object, but virtual object are always accommodated at the imaging plane (figure 2).

Absence of shadow cues: Shadows, like occlusion, provide important depth cues. Shading real and virtual objects with respect to each other touches similar technical problems like the occlusion problem. Bimber et al. discuss and present solutions in the context of optical see-through displays [15].

Further perceptual issues include:

Fixation duration: In virtual scenes the fixation duration is longer than for real scenes. Furthermore, fixations are far more concentrated on moving virtual objects than on real ones. As a result, users in virtual environments generally look less around than in real environments [16].

Errors on distance estimations: Users in virtual environments systematically underestimate the distance to targets. This effect can not be fully explained yet with technical issues [17]. Mohler et al. showed that continuous visual feedback is most important for accurate distant estimations [18].

Hybrid objects are a promising approach to facilitate the interaction in an immersive virtual environment. But they raise several questions: To what extent is the experience acquired by manipulating physical objects applicable to the manipulation of hybrid objects? Are hybrid objects even more useable than physical objects as both the virtual part of the interaction object and the interaction environment are graphically represented? Are hybrid objects perceived as unities? Does active force feedback improve the usability of hybrid objects?

4 Evaluation of Hybrid Objects

We set up a experiment in a Cube, an immersive VR environment with five back projected walls (update rate 84 Hz, estimated system lag 125ms). We examined two interactions with pure physical, pure virtual and hybrid objects in order to compare these three interaction types. Additionally, we used several questionnaires to evaluate the users' opinions, and also tested for spatial sense.

4.1 Hypotheses

Our study addressed the performance with hybrid objects and the user's satisfaction with this interaction technique. Our hypotheses were:

a) Hybrid objects can be manipulated more efficiently than virtual and physical objects in terms of a shorter handling time.
b) Hybrid objects can be manipulated more effectively than virtual and physical objects in terms of a greater accuracy.
c) Hybrid objects provide greater user satisfaction than virtual or physical objects.

The arguments for hypotheses a) and b) are the following: Beside several technological and perceptual issues (see above) physical objects are harder to match with virtual objects in a virtual environment than hybrid and virtual objects because their

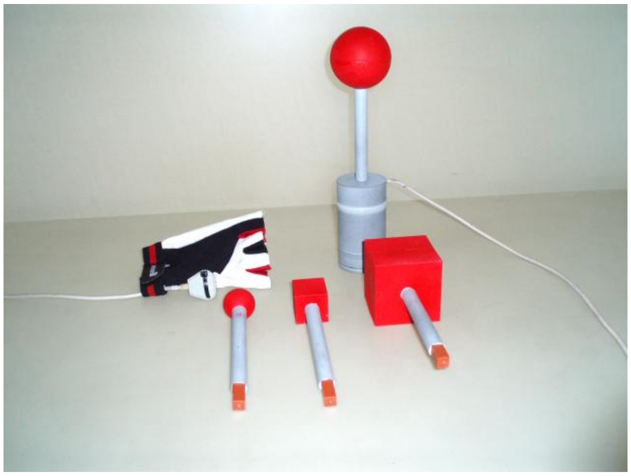

Figure 1. Glove for the virtual condition, handle for both hybrid and physical conditions, reference objects for physical condition.

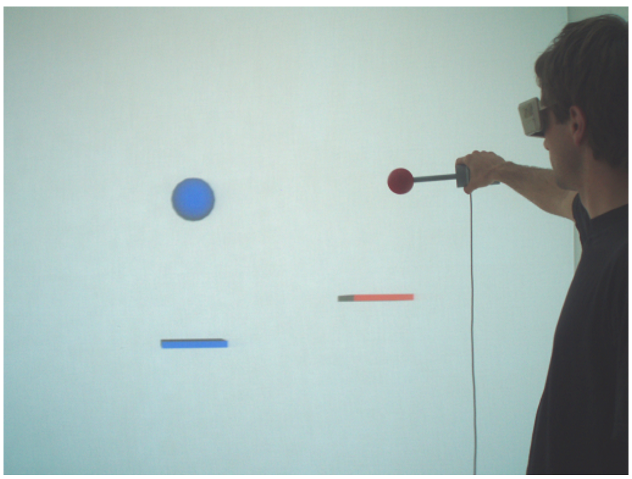

Figure 2. Sphere positioning task with physical object.

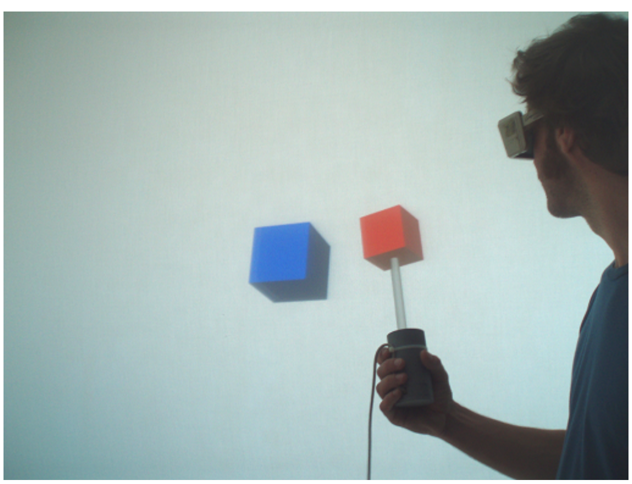

Figure 3. Cube rotation task with hybrid object.

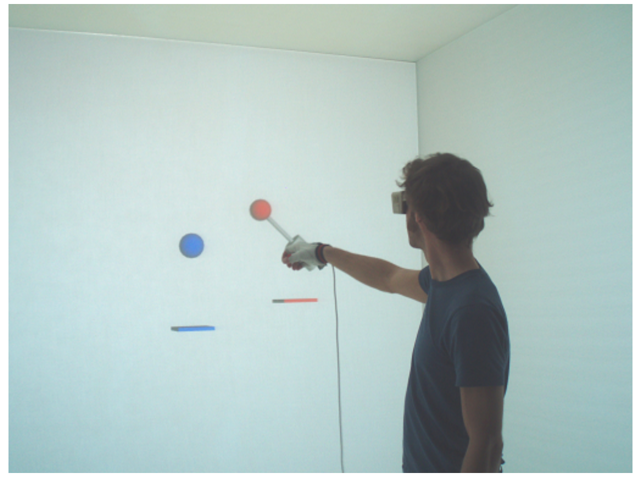

Figure 4. Sphere positioning task with virtual object.

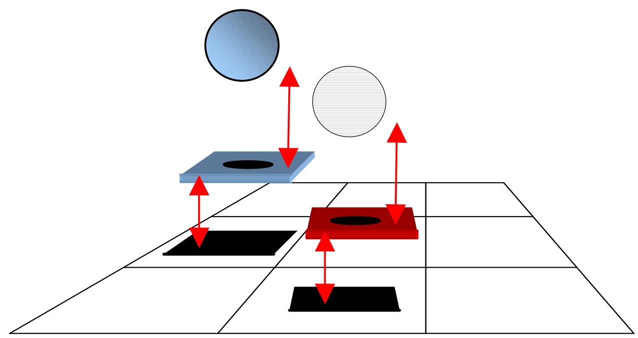

Figure 5. Setup of the positioning task.

visual representation differ significantly. Hybrid objects are manipulatable by a physical part, which affords the application of highly trained, fast and accurate manipulation skills acquired in daily life. Purely virtual objects have only visual affordances and provide no haptic feedback, thus the application of skills requires more cognitive load. The advantages of passive haptic displays (props) or tangible interfaces have been shown in several studies [7, 8, 10]. Our question here was: Are these findings also true for hybrid objects in virtual environments?

Hypothesis c) had no theoretical backing but was based on the hope that users prefer hybrid objects as bridges between the real and virtual environment.

Besides these hypotheses we wanted to examine the following questions:

- Are the hybrid objects perceived as a single entity or do users perceive a virtual-real gap?
- Does the subject's performance (speed, accuracy) depend on the perceived degree of unity?
- Does the subject's satisfaction depend on the perceived degree of unity?

These questions have direct implications for the requirement for appropriate tracking and display technology.

4.2 The Experiments

The goal of the two experiments was to verify the hypothesis that hybrid objects combine the advantages of both pure physical and virtual objects as discussed in the introduction. All three methods were compared in the two different tasks in a within-subject-design.

4.2.1 Subjects

We recruited 36 subjects (18 male, 18 female, mean age 26, *SD*=2.88) who were students at the Technische Universtität Berlin. They were recruited from a university list or by poster, and received compensation. All subjects were right handed.

4.2.2 Interaction techniques

The objects to be manipulated were kept similar under all conditions with respect to color and shape.

In the pure *physical* condition the handle (11 cm long, 6 cm diameter) and the reference objects were real, graspable objects connected by a rod (11 cm to 12.7 cm long) (figures 1 & 2). The subjects were instructed to hold only the handle.

In the *hybrid* condition (figure 3), the handle was graspable, but the rod and the reference object were virtual. We intentionally included the connecting rod in the setup of the hybrid condition although it was technically not necessary. This assured similarity between the conditions, and we further assumed that this setup would help the subjects to regard handle, rod and reference object as a unit.

In the third condition, all parts were *virtual*. A glove (figure 4) was worn, and the virtual object was attached to the palm of the user's right hand and handle, rod and reference object moved according to subject's hand movements. The whole object moved and turned corresponding to how the subjects moved and turned their hand.

The size and color of the handle, the rod and the reference object were maintained in all three conditions. In both the pure physical and hybrid condition, a magnetic sensor (Ascension MotionStar) was placed inside the handle in order to specify the position and orientation of the object, in the virtual condition, the sensor was mounted on the glove.

The glove-based virtual interaction technique provided no means for making use of the fine muscle groups and joints in the fingers. Input devices which provide such interactions have been shown to significantly shorten task completion times [12]. In order to minimize this known effect and to keep the results of our study comparable among all interaction techniques, we chose the palm size grip for the physical and hybrid interaction techniques and asked subjects to hold them tight in their hand during the trials.

Prior to the tests the subjects were allowed to practice both tasks in order to eliminate training effects during the experiment.

Subjects were given two tasks, firstly a cube rotation, and afterwards a sphere positioning task.

4.2.3 Rotation task

The first task was to rotate the reference object (a red cube attached to a handle) so that it had the same spatial orientation as a blue cue cube as this changed orientation in all three dimensions (figure 3). Thus the subjects were to translate the cue cube's orientation to the target cube by rotating the latter in the right way. It did not matter where the reference object was rotated. Overlapping of target and cue cube was to be avoided.

After each trial the cue objects disappeared and the subject was to hold the target object close to a small yellow starting point. The next trial was then started. When the subject kept the object still for at least 1 second and within the movement tolerance of 1° (in rotation) and 1cm (in translation), the position and elapsed time since the start movement was recorded. Differences were calculated between the orientation of the cue object and target object in respect to x, y, and z axes of the global coordinate system. The overall error for each trial was calculated as the sum of these three errors (which is not the smallest angle that is required to rotate the object to the target orientation as in [4]).

The cue cube's position was not altered but kept constant in the center of the visual field since position effects were examined in the other task and only orientation effects were of interest here. In order to eliminate size effects, subjects were to execute 6 trials each with a large cube of 7 cm and small cube of 3.5 cm edge length. The subjects underwent the trials with all three interaction techniques whereas the sequence of the techniques was varied among all subjects.

4.2.4 Positioning task

The sphere positioning task used a red reference object (the sphere) which has to be positioned at the same distance above a target square area as the cue sphere is positioned above the cue square area (both blue). Thus the subjects first had to estimate the distance between the cue sphere and the cue area and to move the sphere according to this distance above the target area.

The target and cue areas were assigned to different positions on a 3 x 3 array. The heights relative to the array of both cue and target area also differed independently from trial to trial. The height of the cue sphere was altered, too (figure 5). Consequently a trial condition is defined by the position and height of the target area, the position and height of the cue area, and the height of the cue sphere. We applied 6 different trial conditions under which these factors were well balanced. Similar to the first task, the subjects underwent the trials with all three interaction techniques and the order of the techniques was varied among all subjects. Again the subjects were told to hold the reference object close to the yellow starting point between trials.

Time measurements were similar to the first task. The error was calculated in the deviation between cue object's and target object's position in respect to x, y, and z axes of the global coordinate system. The overall error for each trial was calculated as the sum of these three errors (differing from [19]).

4.2.5 Questionnaires and additional experimental material

In order to compare the three interaction techniques in terms of user satisfaction, perceived unity of interaction objects, task difficulty etc., we developed a questionnaire with ten items per interaction technique and seven items per task.

We also used the "AttrakDiff" questionnaire of Hassenzahl [20, 21]. This goes beyond standard usability questionnaires in that it not only measures user-perceived usability in terms of *pragmatic*, functional quality. It also provides means for measuring *hedonic* attributes of interactive products, namely *stimulation* by the product and *identification* with the product. *Stimulation* is related to the human need for developing its personality and gaining new skills and knowledge. *Identification* stands for the users' need to express themselves through objects and to communicate their own personality to others, e.g. by certain products. These human needs and wants are important for the overall user experience of a product, or, as in our case, of interaction techniques.

At the very end of the experiment, a test was carried out of spatial sense, the "3D Cube Test" (3DW) [22]. The performance in this test was used to determine the spatial sense effect and to deduct this from the performance in the tasks but also to examine relations between spatial sense and user satisfaction.

A questionnaire surveying personal information as well as personal experience with 3D games, joysticks, virtual environments, and CAD software was presented before the experiments, all other questionnaires were presented afterwards.

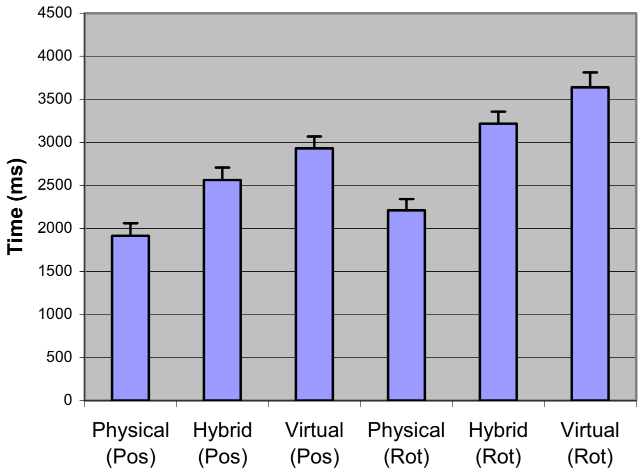

Figure 6. Speed of positioning and rotation tasks.

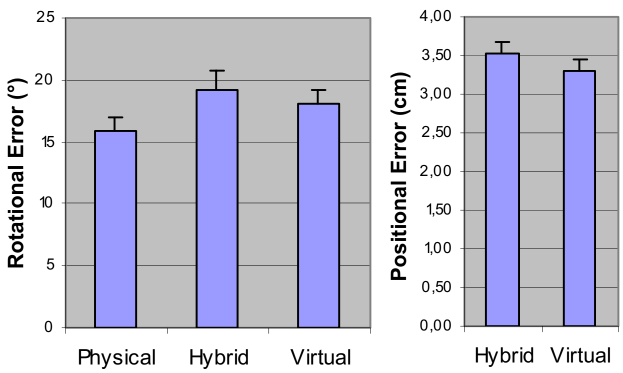

Figure 7. Errors of positioning and rotation tasks.

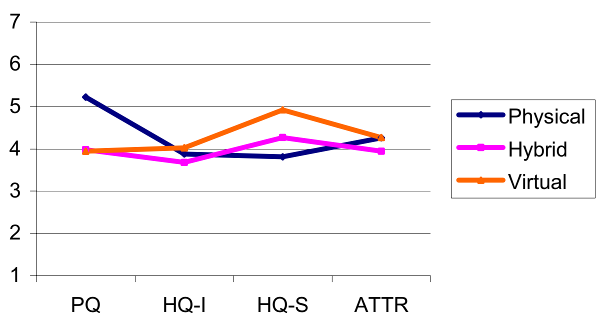

Figure 8. Results of the "AttrakDiff" questionnaire, showing pragmatic (PQ), hedonic identification (HQ-I), hedonic stimulation (HQ-S) qualities, and overall attractiveness (ATTR) of physical, hybrid, and virtual interaction techniques.

Experience was measured to determine and to deduct the experience effect from the performance in the tasks.

4.3 Results

4.3.1 Rotation task

We compared speed (time) and accuracy (error) for both tasks between the three conditions by means of a repeated measure ANOVA (figures 6 and 7). In the rotation task, we found significant differences in speed between the three conditions ($F(2,35)=70.61$; $p<.001$). The physical condition was the fastest (M=2211ms, SD=133.00ms), significantly faster than both the hybrid condition (1005ms) and the virtual condition (1430ms). The hybrid condition was the second fastest (M=3216ms; SD=142.59ms), significantly faster than the virtual condition (424ms). The virtual condition was the slowest interaction technique (M=3640ms; SD=174.01ms).

For accuracy (error), the results also differed significantly ($F(2,35)=6.56$; $p<.01$). The physical condition was the most accurate (M=15.83°; SD=1.20°), significantly more accurate than the virtual condition (2.30°) and significantly more accurate than the hybrid condition (3.38°). The virtual condition was second most accurate (M=18.14°; SD=1.068°), but the difference to the hybrid condition was not significant. The hybrid condition was the least accurate interaction technique (M=19.21°; SD=1.57°).

4.3.2 Positioning task

In the positioning task we again found significant differences for speed between the three conditions ($F(2,35)=65.52$; $p<.001$). The physical condition was the fastest (M=1914ms; SD=144.92ms), significantly faster than the hybrid condition (650ms) and significantly faster than the virtual condition (1016ms). The hybrid condition was the second fastest (M=2564ms; SD=144.10ms), significantly faster than the virtual condition (366ms). The virtual condition was the slowest interaction technique (M=2930ms; SD=139.49ms).

The accuracy (error) also differed significantly ($F(2,35)=39.75$; $p<.001$). The virtual condition was the most accurate (M=3.3cm; SD=0.2cm), 0.2cm less than the hybrid condition (however not significant). The hybrid condition was second most accurate interaction technique (M=3.5cm; SD=0.1cm). The physical condition showed significantly lower values (M=6.2cm, SD=0.4cm), but could not be compared to the other conditions due to high position tracking errors. In the other conditions this error did not occur because users concentrated on the virtual reference object and not on the tracked physical handle or glove. However they noticed the gap between glove or handle and virtual object parts due to the tracking error (see discussion).

4.3.3 AttrakDiff

Figure 8 summarizes the results of the "AttrakDiff" questionnaire. We found significant differences between the conditions in the pragmatic quality ($F(2,35)=44.77$; $p<.001$), hedonic stimulation quality ($F(2,35)=55.22$; $p<.001$):

The *pragmatic quality* of the physical object was highest (M=5.22, SD=0.55). It was followed by hybrid (M=3.98, SD=0.86) and virtual objects (M=3.95, SD=0.95). The differences between hybrid and virtual objects were statistically not significant.

The *hedonic stimulation quality* of virtual objects (M=4.92, SD=0.56) was rated higher than those of hybrid (M=4.27, SD=0.63) and physical objects (M=3.81, SD=0.47).

The differences in the hedonic identification quality and attractiveness were statistically not significant:

The *hedonic identification quality* of virtual objects (*M*=4.03, *SD*=0.67) was rated higher than those of physical (*M*=3.88, *SD*=0.52) and hybrid objects (*M*=3.68, *SD*=0.79).

The *attractiveness* of virtual objects (*M*=4.27, *SD*=0.69) was rated almost equal higher than those of physical (*M*=4.26, *SD*=0.69) and hybrid objects (*M*=3.94, *SD*=0.77).

4.3.4 Perceived object unity, control, personal experience

The perceived object unity differed significantly among the three conditions ($F(2,35)=45.70$; $p<.001$). The unity of hybrid objects was perceived as medium (*M*=2.69, *SD*=1.24) on an interval scale ranging from 1 to 5, significantly less than both physical objects (*M*=4.86, *SD*=0.35) and virtual objects (*M*=4.25, *SD*=1.02).

The results for the item "I was able to control the VR well with this interaction technique" differed significantly ($F(2,35)=5.07$; $p<.05$). On an interval scale ranging from 1 to 5, the physical condition was rated best (*M*=3.78, *SD*=0.87), followed by the hybrid (*M*=3.25, *SD*=0.73) and the virtual condition (*M*=3.19, *SD*=0.89). However, the differences between hybrid and virtual condition were not statistical significant.

Out of 36 subjects, 13 declared much to very much personal experience with either 3D games (2), joystick use (3), or CAD software (9). None had much experience with virtual environments. We found no statistical effects between the results of either the 3DW, personal experience, or the perceived unity of hybrid objects on the one hand and the subject's performance, accuracy, and pragmatic and hedonic qualities on the other hand..

4.4 Discussion

The experiments show that physical objects are best suited for basic manipulation tasks with respect to speed and accuracy (for a rotation task). Our hypotheses regarding the superiority of hybrid objects in terms of efficiency, effectivity, and user satisfaction were not met. Nevertheless hybrid objects significantly outperformed virtual objects regarding manipulation speed (hypothesis a). We found no statistical differences between hybrid and virtual objects regarding the accuracy of task solving (hypothesis b). User satisfaction (hypothesis c) showed advantages for hybrid objects only in one dimension compared to physical objects.

4.4.1 Hypothesis a: Efficiency

Manipulation of the virtual object was slowest, which is consistent with the findings of Ware and Balakrishan. [19], who found that speed depends primarily on the display update rate, which is infinite for physical objects, and lag, which is almost zero for physical objects. Interestingly, the partly physical nature of the hybrid object led to 8.8 percent faster manipulations compared to the virtual object. We think this is due to the passive haptic feedback during the movement, which might provide additional cues about the object's position. The differences in speed for the rotation task between the physical and hybrid (1005ms) and the physical and virtual condition (1430ms) were two to three times as high as the differences between the physical and virtual condition in the study of Ware and Ross (450ms) [4]. A very likely explanation for this is the 25 to 50ms higher system lag in our study, which can have multiple effects in closed eye-hand coordination feedback loops [19]. Furthermore subjects in our study had to conduct larger rotation movements, because our objects (handles, rods and reference objects) were larger (up to 29 cm) compared to objects in the study of Ware and Ross (13 cm).

4.4.2 Hypothesis b: Effectivity

We had expected manipulation of the hybrid object to be the most accurate, because its reference object was represented the same way as the cue objects. We also expected the physical handle of the hybrid object to provide more precise means for orientation and positioning than the virtual object. But the results show that it offered no advantage compared to the virtual object and was significantly less accurate than the physical object. We think that a noticeable gap between handle and rod of the hybrid object, which was mentioned by six participants, led to poor accuracy. We see potential to increase user performance by better alignment of virtual and real parts of hybrid objects, e.g. by means of optical tracking. However, perceived unity of hybrid objects showed no statistical effect on either speed or accuracy.

It remains an open question if subjects' eye preference affected the results. All subjects were right-handed, it is to assumed that one third was left-eyed [23]. Eye dominance has an effect on the performance of visual search tasks [24], but its overall function in binocular vision is still unclear [25]. Our experimental setup with a within-subject-design, in which all subjects underwent the trials with all three interaction techniques in varied sequences, should have limited potential effects. Nevertheless, future research should either exclude subjects with mixed eye and hand dominance or investigate its effects.

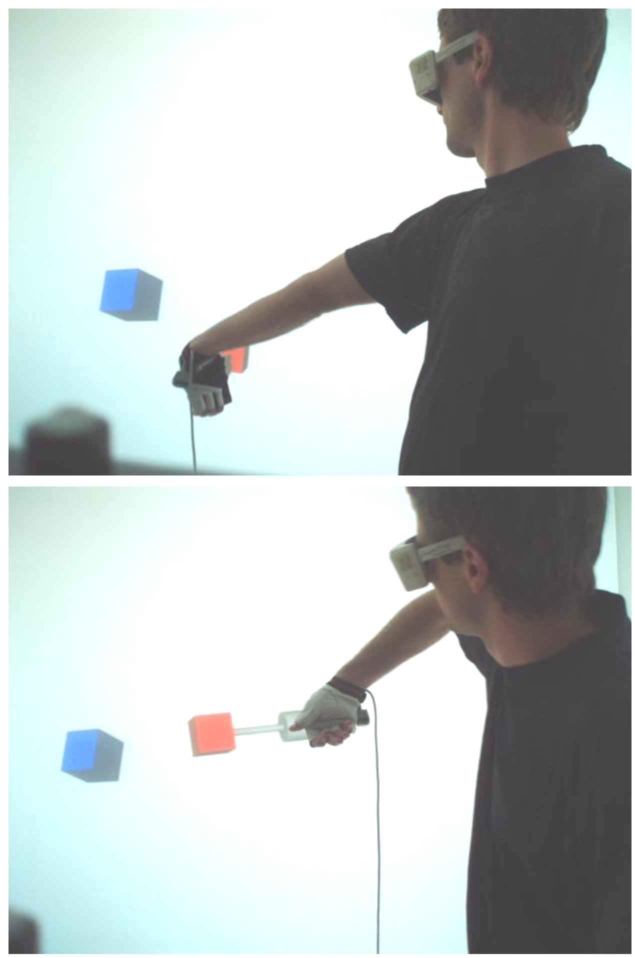

Figure 9. Awkward hand postures in rotation task with virtual object (posed).

4.4.3 Hypothesis c: User satisfaction

One subject reported “I most like the hybrid object. I had something in my hand but am also part of the virtual.” However the AttrakDiff questionnaire shows that most subjects found the physical object best suited for fulfilling the tasks (in correspondence to the real performance data). Hybrid objects seem to gain some stimulating effects from their partly virtual representation (dimension HQ-S). As for improving the accuracy, we think better alignment and wireless tracking will increase attractivity of hybrid objects.

4.4.4 Personal experience

The fact that we found no statistical effects from personal experience with computers suggests that interaction in our experiment differed from common 2D/3D interaction techniques and were probably close to everyday object manipulations. This is interesting especially for the relatively large number of subjects with much or very much CAD experience (25 percent of the subjects). Because of the small number of subjects with much 3D game experience (2) we could not conclude effects depending on this factor. This is in contrast to other studies on VR interaction techniques, e.g. [26], who found correlations between user experience with 2D/3D graphics, and fun computer use and trial times in raybased selection tasks. A speculative explanation could be that theses interaction techniques were more artificial, computer oriented and required more prior computer experience.

4.4.5 Awkward hand postures

An interesting finding during the study was that some subjects showed awkward, non-ergonomic hand postures when searching for the correct orientation in the rotation task, especially in the training phase (figure 9). We found that this happened mainly in the virtual condition, very few times in the hybrid and almost never in the physical condition. The exclusive use of major muscle groups in the virtual condition might be partly responsible for this effect [12].

Similar findings were reported by Wingrave et al. who analysed raybased selection techniques using data gloves and head mounted displays (HMDs) [26]. They observed that subjects rotated their shoulders back and bent their wrists. Like in our study, such behavior fell off with practice.

We believe that the multisensory experience of holding physical objects leads to instant activation of natural motion patterns, which might be missing when using purely virtual objects. We see a qualitative difference in the affordances of virtual and physical objects. Again, hybrid objects might benefit from their partly physical representation.

5 Conclusion and Future Work

Investigating the usability of hybrid objects for basic manipulation tasks, namely rotating and positioning, in virtual environments, we were able to show that users perform significantly faster with hybrid objects than with virtual ones, but we found no improvement in terms of accuracy (error). Entirely physical objects are by far the fastest and (at least for rotating) the most accurate. This result again underlines the benefits of props in virtual environments [7, 8].

We think that technical improvements, most importantly eliminating the noticeable gap between handle and rod, may further improve performance and user satisfaction of hybrid objects.

Concerning further improvement of hybrid objects, beside improving display and tracking technology, we see the following research questions:

- What influences the perception of unity of hybrid objects, what are possible variations? Is a visual connection between the parts (in our case the rod) necessary or helpful?
- Do users tend to grasp, manipulate, and release hybrid objects more often than virtual objects for comparable tasks?
- What are the optimum numbers of hybrid objects for certain tasks (physical clutter [27])?
- Does active force feedback improve usability of hybrid objects [28]?
- Would the results of our study differ if the target object were physical and not virtual?

This study supports the view that hybrid objects can serve as an alternative to current VR interaction techniques. They are especially advantageous in applications where ergonomic issues and objects flexibility are crucial, e.g. product design, information management, and system control. However, certain problems, especially relating to alignment, remain to be solved.

Acknowledgement

Primary support for this work has come from the Fraunhofer Institute for Production Systems and Design Technology Berlin. This research project is also part of the research training group prometei program and financed by the German Research Foundation (DFG, project number 1013).

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