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ORIGINAL ARTICLE

# An evaluation of asymmetric interfaces for bimanual virtual assembly with haptics

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**Abstract** Immersive computing technology provides a human–computer interface to support natural human interaction with digital data and models. One application for this technology is product assembly methods planning and validation. This paper presents the results of a user study which explores the effectiveness of various bimanual interaction device configurations for virtual assembly tasks. Participants completed two assembly tasks with two device configurations in five randomized bimanual treatment conditions (within subjects). A Phantom Omni® with and without haptics enabled and a 5DT Data Glove were used. Participant performance, as measured by time to assemble, was the evaluation metric. The results revealed that there was no significant difference in performance between the five treatment conditions. However, half of the participants chose the 5DT Data Glove and the haptic-enabled Phantom Omni® as their preferred device configuration. In addition, qualitative comments support both the preference of haptics during the assembly process and comments confirming Guiard's kinematic chain model.

**Keywords** Haptic devices · Virtual reality · Interaction devices · Interaction techniques · Human–computer interaction (HCI) · Bimanual interaction

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## 1 Introduction

Understanding product assemblies is important throughout the development and life cycle of a product. Virtual assembly employs cutting edge hardware in the creation, design, and evaluation of assemblies. As part of this technology, bimanual haptics renders realistic force feedback to create an immersive experience for manipulation. Bimanual haptic applications have been used for a wide variety of purposes from explosive ordnance disposal (Kron et al. 2004), to surgical training (Hinckley et al. 1998) and surface and curve manipulation (Owen et al. 2005; Shaw and Green 1994). They have also been used for 3-D object manipulation and interaction in virtual environments (Balakrishnan and Kurtenbach 1999; Bowman and Hodges 1997; Poupyrev and Ichikawa 1999). Fiorentino et al. (2010) found that the incorporation of bimanual haptics aided CAD designers in model creation. Talvas et al. (2013) describe a wide range of bimanual haptic interaction techniques

Bimanual virtual assembly has been found to outperform unimanual virtual assembly in a variety of situations, including perception of weight (Giachritsis et al. 2009; Owen et al. 2005), virtual navigation for the visually impaired (Crossan and Brewster 2006), and cooperative tasks (Gunn 2006; Hinckley et al. 1997). The increased performance of bimanual assembly has been explained using a framework that models the two hands as two motors connected in series. This model, known as the kinematic chain model (Guiard 1987), emphasizes an asymmetric division of labor between the two hands where the dominant hand moves in reference to the non-dominant hand. An asymmetric task is a task in which each hand does a uniquely different task while a symmetric task is where each hand does the same task. For example, simultaneously opening two oppositely hinged cupboard doors is a symmetric task while dealing playing cards is an asymmetric task.

Studies of asymmetric and symmetric bimanual tasks have resulted in a series of insights into the way humans use both hands when completing various tasks. According to Hinckley et al. (1997), bimanual interaction is optimal when each hand assumes its most effective role. In a 2-D bimanual symmetric tracking task, divided attention, task difficulty, and a lack of visual integration can decrease performance (Balakrishnan and Hinckley 2000). However, the most common bimanual interaction is one in which the non-dominant hand is responsible for gross motor movements while the dominant hand performs more fine motor positioning (Hinckley et al. 1998; Marteniuk et al. 1984). Supporting research indicates that the non-dominant hand is generally used for lower-frequency and higher-amplitude movements and the dominant hand is used for higher-frequency and lower-amplitude movements (Peters 1985). This has led to research into the use of devices for bimanual assembly in virtual reality.

Vyawahare and Vance (2009) proposed a bimanual device configuration that incorporates haptic feedback by using a position-tracked glove on the one hand and a haptic device on the other hand. Referencing Hinckley's model of bimanual interaction, the glove (non-haptic) would be placed on the non-dominant hand and be used to select and position virtual objects and the haptic device would be controlled by the dominant hand where the user would perform fine positioning movements. The main benefit in implementing this configuration is that the user is able to feel haptic feedback during crucial assembly operations and able to reach parts beyond the haptic workspace. In this way, task performance in the configuration supports haptic, kinesthetic, and visual representation of the bimanual assembly process.

A more recent paper outlines a similar asymmetric interface using haptics and a Razer Hydra™ (Vyawahare and Stone 2012). The Hydra provides two controllers with button and joystick input on each controller that are tracked using a magnetic tracking base. Originally created and marketed for video games, the Hydra has been adopted and extended by virtual reality researchers as a tracking and input device. Vyawahare and Stone used the large workspace of the Hydra to augment the interaction method and provide asymmetric interaction. An evaluation of this interface and the interaction method was performed and the utility of these methods was shown to be useful for a variety of tasks (Vyawahare and Stone 2013).

The desire to use one haptic device rather than two for desktop assembly is motivated by three factors. The first of these is cost reduction. Adding haptic force feedback to a simulation increases the cost because of the need for additional equipment. If the use of a haptic device coupled with a non-haptic device yields similar or better performance than two haptic-enabled devices, costs would be reduced by choosing the less expensive configuration. Vélaz et al. (2014) explored three different hardware configurations for bimanual virtual assembly. Their results indicated that a hybrid configuration of a haptic device on the one hand and a non-haptic device with markerless motion capture on the other hand produced the shortest time of completion for the assembly task. They concluded that the hybrid configuration was sufficient to perform virtual assembly of parts where precision fit is not critical. The research presented here compliments their work by exploring a reduced-cost configuration for bimanual assembly of precision fit parts.

The second factor is the desire to improve realism. Replacing a haptic probe with a glove provides the user with the visual representation of finger motion during grasping. However, most current glove interfaces do not have haptic feedback, but support more natural hand motion and interaction than existing haptic devices. Instead of learning how to use an entirely new device, a user can grab, select, and release objects when wearing the glove in a manner similar to the way they would handle objects in the real world.

Finally, desktop haptic devices have limited workspaces. Talvas et al. (2013) point out that this limitation can be addressed by developing unique software algorithms or by using unique hardware configurations. One software algorithm that expands the usable haptic workspace is the bubble technique proposed by Dominjon et al. (2005) and modified to accommodate bimanual interaction by Talvas et al. (2013). This technique provides the user with an intuitive means of essentially moving the haptic device within the entire virtual environment, allowing for haptic interaction at any place within the environment without the need for haptic clutching. Pavlik and Vance (2015) expanded on the bubble technique to allow grasping parts with the haptic device while simultaneously moving within the environment. Other techniques such as scaling the virtual environment (Fischer and Vance 2003) and haptic clutching (Isshiki et al. 2008) have also been investigated.

The study described in this paper is an evaluation of the Vyawahare and Vance (2009) proposed bimanual device configuration for precise fit haptic assembly. Two different assembly tasks are performed using various combinations of desktop haptic devices and a position-tracked glove.

## 2 Methodology

### 2.1 Software

The application was developed using SPARTA (Scriptable Platform for Advanced Research in Teaching and

Assembly). SPARTA combines VR Juggler (VRJuggler 2013) for stereoscopic rendering and position tracking management, OpenSceneGraph (OpenSceneGraph 2013) for graphics, Voxmap PointShell (VPS) (McNeely et al. 1999) for physics calculations, and VR JuggLua (Pavlik and Vance 2011b) for easy scripting and content creation. SPARTA supports multiple input and output devices including position trackers, stereo glasses, stereo projection systems, gloves and haptic devices (Pavlik and Vance 2011a). It was developed by researchers at the Virtual Reality Applications Center at Iowa State University.

## 2.2 Hardware

The two hardware devices that were used in this study are the Phantom Omni® haptic device and the 5DT Data Glove 5 Ultra. The Phantom Omni® is priced around $2000 USD and the 5DT Data Glove 5 Ultra is priced around $995 USD. The Phantom Omni® provides the ability to enable or disable haptic force feedback while the glove does not have haptic force feedback . For completeness, we included the haptic disabled Omni device configuration in our treatments.

The user wore position-tracked stereo glasses to view the rear projected stereo image on the desktop screen. The glasses were tracked using an InterSense IS-900 hybrid inertial and ultrasonic tracking system. The gloved hand was tracked using a Polhemus Patriot magnetic tracker. Both commercial tracking systems have low latency with the IS-900 at around 4 ms and the Patriot at around 17 ms.

Interaction using the Omni allows the user to have a full 6 degrees of freedom (DOF) in tracking and movement, along with three DOF haptic force feedback (see Fig. 1). The user's interactions in this study consisted of moving a virtual cursor around the scene. Once the cursor intersected a part, the part turned slightly transparent indicating that it could be selected. A button on the Omni could then be pressed to select the part and subsequent movement would move the virtual part.

Interaction using the 5DT glove was similar to the Omni, also providing six DOF in tracking and movement; however, no forces are rendered to the user's hand

Fig. 1 Dual Phantom Omni® configuration

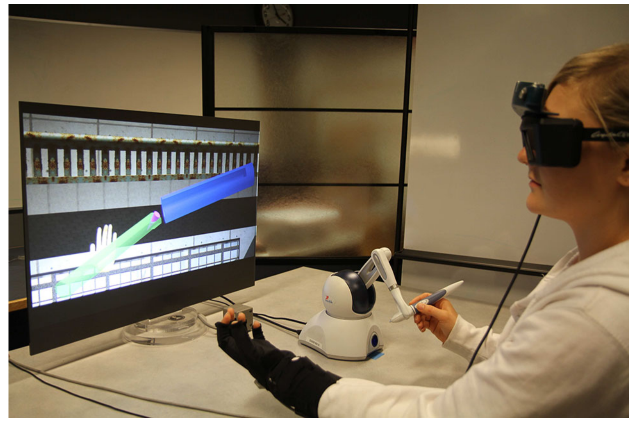

Fig. 2 Desktop setup showing the 5DT Data Glove and the Phantom Omni® configuration

with the Data Glove (see Fig. 2). In this interaction, a virtual hand representation acted as a cursor that could be moved around the scene. Intersection of the virtual hand with a part turned the part slightly transparent indicating that it could be selected. The user then made a fist gesture to grab the part and move the virtual part in the environment.

The six DOF movement and tracking of both systems provides a natural interaction that mimics real physical assembly. No scaling of movement was applied to either device to ensure that it matched real-life interaction.

## 2.3 User study

### *2.3.1 Study design*

The two independent variables were the device configurations (five treatment conditions) and the task difficulty (easy and hard). The dependent variable was performance as measured by task completion time. Examining the effect of device configuration on performance time was a within-subject variable. Task difficulty was a between-subject variable. The five device configurations are listed in Table 1.

Each participant was randomly assigned to one of the two task difficulties and asked to perform the assembly using each of the five treatment conditions. The order of the five treatment conditions was randomized to account for fatigue and learning. The easy task consisted of insertion of one virtual object into another (Fig. 3). This required orientation and insertion of the object. The difficult task required object orientation, insertion, rotation, and finally insertion (Fig. 4). This task is similar to the insertion of a key into a lock, followed by rotation of the key in the lock.

**Table 1** Treatment conditions

| Condition | Dominant hand | Non-dominant hand |
|---|---|---|
| 1 | Omni (haptics disabled)* | Omni |
| 2 | Omni | Omni |
| 3 | Omni | Omni (haptics disabled)* |
| 4 | Omni | Glove |
| 5 | Glove | Omni |

* Referred to as NoHaptic Omni

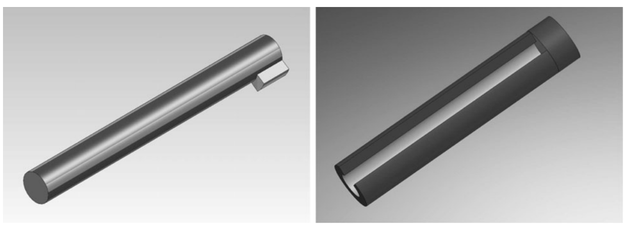

**Fig. 3** Unassembled individual objects for the easy task

The assembly of these two simple parts was designed to represent common motions of assembly. Sliding a pin into a sleeve is a common motion that occurs in many assembly operations. In a virtual environment, this is more difficult than in real life, especially if the virtual environment does not impose artificial axial constraints between the two parts. The motion of rotation can also be difficult to perform in virtual reality due to the existence of a virtual spring between the haptic device and the rigid body combined with the need to rotate and re-grasp.

Upon arriving, participants filled out a consent form. Participants then completed a short pre-study questionnaire that gathered basic demographic information along with a self-assessment of previous computer and VR experience. Next, participants watched a short video demonstrating the equipment that they would be using and the interface for interacting with the virtual parts. Participants were given two minutes to become familiar with using the equipment and the application. Different models than the test models were used during this practice period and all participants used the Omni in their dominant hand and the 5DT Data Glove in their non-dominant hand. This let participants experience both hardware devices. Next, the timed data were gathered as participants used each of the five randomized device configurations to perform the assigned task. The piece that resembles a key was always placed on the left in the scene and the other piece was placed on the right. For each configuration, they were instructed to complete the assembly twice. In total, each participant completed ten assembly operations. A picture of the disassembled and assembled objects was placed on the table for reference but no other instructions were given

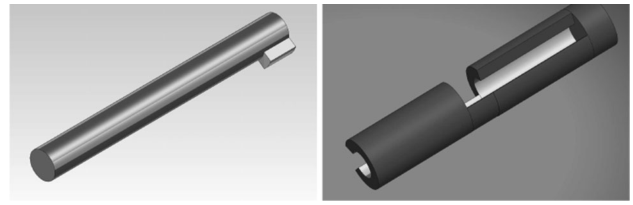

**Fig. 4** Unassembled individual objects for the difficult task

during the treatments. Upon completion of the trials, participants completed a short exit questionnaire to gather preferential data.

### 2.3.2 *Participants*

Fifty-two participants (39 males and 13 females) completed the study. While participants were not compensated, some did receive class credit. The participants were recruited mostly from undergraduate engineering and psychology classes. The ages ranged from 17 to 36 years with a mean ($M$) of 22.17 and a standard deviation (SD) of 4.48. Forty-eight participants were right-handed and four participants were left-handed. No participants indicated that they were ambidextrous. The participants were divided into two groups (easy task and difficult task) resulting in 26 participants in each group. Self-reported computer experience was reported on a Likert scale between 0 (no experience) and 10 (high computer experience) ($M = 5.73$, SD = 2.57). Most of the participants had little experience with virtual reality as was self-reported on a Likert scale between 1 (none or little experience) and 10 (significant experience) ($M = 2.94$, SD = 2.38). Prior experience was low as self-reported on a Likert scale between 1 (none or little experience) and 10 (significant experience) regarding both virtual assembly operations ($M = 2.01$, SD = 1.79) and haptic force feedback devices ($M = 1.67$, SD = 1.2).

Within the participant pool, there was a significant difference in self-reported computer experience between males and females. The results of an independent two-sample $t$ test, $t(50) = -2.70$, $p = 0.009$ indicated a significant difference between groups with males reporting their computer experience as being higher than females.

## 3 Results

### 3.1 Quantitative

For each treatment, the participants completed the assembly task twice. For purposes of data analysis, the overall completion time was calculated as the average of the two task times. A comparison of task completion time for each treatment is shown in Fig. 5.

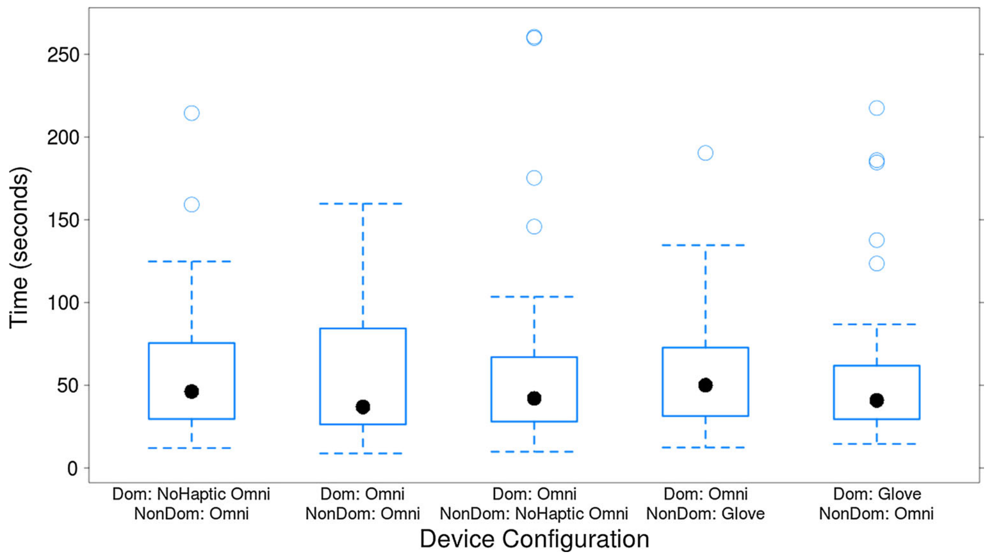


**Fig. 5** Average task completion times for each device configuration

In order to run a balanced ANOVA, five participants who did not finish all five device configurations because of a technical glitch were removed. All five of these participants were right-handed. This left 47 participants who completed all the device configurations. Levene's test was not significant $F(4, 230) = 0.39$, $p = 0.81$ signifying that the assumption around equality of variances was not violated. The results of an Omnibus ANOVA were not significant, $F(4, 184) = 0.10$, $p = 0.97$, indicating that there was little difference in performance between the different treatments not including the variable of task difficulty. When including the interaction of task difficulty in comparing the five treatments, this was also not significant, $F(4, 1739) = 0.41$, $p = 0.80$. Since the Omnibus ANOVA was not significant, more specific planned linear contrasts that would examine the details of individual device configurations could not be performed. The effect of devices used during the practice session at the beginning was not considered in the analysis since all participants used the same configuration.

In examining the total time taken to finish the tasks between the easy and difficult task assignments, there was a significant difference when running an independent two-sample $t$ test, $t\ (233) = -4.36$, $p < 0.001$ with the more difficult task taking longer.

Irrespective of treatment, in general, the participants exhibited a slight learning effect as they progressed through the study (Fig. 6). In particular, the increase in their performance from the first task that they completed to the second task is evident.

There was no significant difference in the total time taken to finish the task between groups of left-handed and right-handed participants, $t(233) = -1.41$, $p = 0.16$ irrespective of task difficulty.

In comparing the time taken to finish the tasks between males and females, there was a significant difference when running an independent two-sample $t$ test, $t(66.22) = 5.34$, $p < 0.001$ with males participants completing the task faster. The results are shown in Fig. 7.

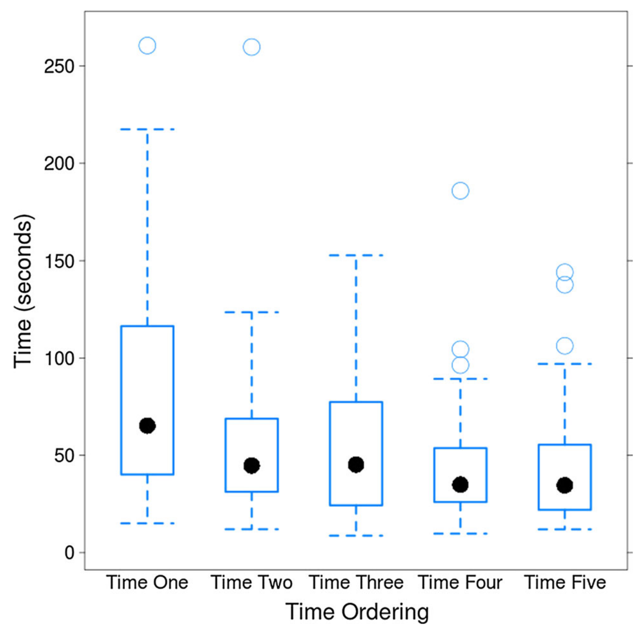


**Fig. 6** Times for each of the five trials regardless of device configuration and task assignment

In the exit questionnaire, participants were asked to pick their preferred device setup from any possible combination of bimanual or unimanual device combinations and dominant or non-dominant hand. There was little difference based on handedness preference; therefore, these groupings were combined and a summary of the responses is presented in Table 2. Given the multitude of possible device combinations and the low number of participants, a Chi-squared goodness of fit test was not performed.

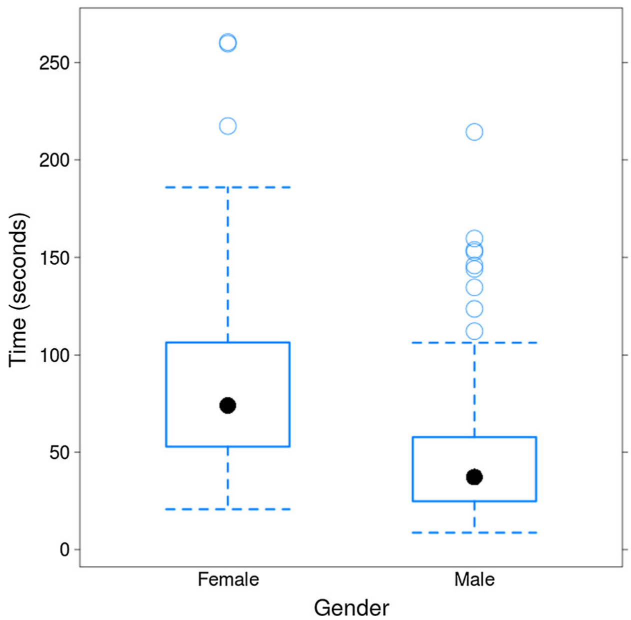


**Fig. 7** Differences in time taken based on gender

**Table 2** Preferred device combinations

| Dominant hand | Non-dominant hand | Number of participants |
|---|---|---|
| Omni | Glove | 15 |
| Omni | Omni | 12 |
| Glove | Omni | 11 |
| Glove | Glove | 4 |
| Glove | NoHaptic Omni | 3 |
| Omni | NoHaptic Omni | 2 |
| Glove | No device | 1 |
| NoHaptic Omni | Glove | 1 |
| NoHaptic Omni | Omni | 1 |
| No device | Omni | 1 |
| No device | Glove | 1 |

While participants were not able to try every possible bimanual or unimanual device configuration, they were able to experience both the Glove and Haptic/NoHaptic Omni. Interestingly, the majority of participants preferred at least one haptic device (42 out of 52 responses) as given in Table 2. Twenty-six of the 52 participants chose the Glove and the Omni. Additionally, participants rated the use of haptic force feedback beneficial in assembling the objects on a Likert scale between 1 (useless) and 10 (useful) ($M = 7.55$, SD = 2.06). They also rated each of the devices on a Likert scale for helping in the assembly process: Omni ($M = 7.26$, SD = 2.03), NoHaptic Omni ($M = 5.36$, SD = 1.84), and Glove ($M = 6.55$, SD = 2.65).

In general, participants had a favorable view of the hardware being useful in day-to-day use when asked to rate it on a Likert scale between 1 (useless) and 10 (useful) ($M = 6.82$, SD = 1.98). Almost three-fourths of the participants (72 %) said that if the technology was available they would use it daily. Most (71 %) felt the haptic force feedback increased their ability to assemble the objects with some (12 %) saying it decreased their ability and others (17 %) saying it had no effect. When asked about the use of the haptic device in their dominant hand and their ability to assemble the objects, it was gauged as being quite helpful ($M = 7.94$, SD = 1.92). Multiple devices were also considered to be quite helpful in the overall simulation experience ($M = 7.32$, SD = 1.99). When asked how natural they felt their interactions with the environment seemed, participants had a favorable view ($M = 6.84$, SD = 2.14) and in addition they felt that the sense of moving around was compelling ($M = 7.48$, SD = 1.70). In general, the virtual reality experience was deemed moderately realistic when compared to the real-world experience of assembling the objects ($M = 6.07$, SD = 1.93).

### 3.2 Qualitative

The benefit of this study design was that it gave participants experience with many device configurations and they were able to try both haptic and non-haptic devices. This helped temper their qualitative comments and responses. The last section in the final exit questionnaire was open-ended and asked participants if they had any comments about their overall experience. In general, participants had a favorable opinion and seemed to prefer the haptic Omni as given in the comments in Table 3. In addition, comments from participants seemed to echo the theory of the kinematic chain model as given in Table 4.

In general, participants were supportive of the experience saying that they, "enjoyed it." One participant said, "I thought it was awesome! I thought once I got the hang of how to do it that it was a lot of fun to work with! I am amazed that this is possible!". Participants even thought of additional use cases for the devices besides virtual assembly such as gaming. One participant said, "The device is great and I hope this device can be obtained at an affordable price because I know people in my country with drawing and designing objects would have their work time lightened with this piece of technology".

## 4 Discussion

Although not shown to be statistically significant, the study results show that the use of the Glove in the non-dominant hand and the Omni in the dominant hand for bimanual assembly resulted in similar performance when compared to the other configurations that were tested for this specific

**Table 3** Participant comments regarding device preference

| Participant | Comment |
|---|---|
| 110847 | "Used right hand (dominant) more. Force better then no-force" |
| 133659 | "Use with or without haptic to line them up, use with haptic to assemble. I had difficulty with depth, need haptic and change in image to find where the cursor was relative to the objects" |
| 90411 | "The Omnis felt a lot more natural than the gloves" |
| 131542 | "I felt that the Phantom Omni was especially helpful because I had more fine control over the objects" |
| 141417 | "The glove was harder to use than the Phantom Omni and when the haptic force was enabled it felt easier to work" |
| 151438 | "The haptic disabled Phantom Omni was more difficult to use than the haptic-enabled Phantom Omni" |

**Table 4** Participant comments confirming kinematic chain

| Participant | Comment |
|---|---|
| 102315 | "Working with two Omnis was challenging. I'd prefer to use only one. When haptic feedback was given to my non-dominant hand, it was more challenging. Haptic feedback was useful in dominant hand. The glove was very natural to use and worked well for both hands" |
| 110324 | "The difficult one was the 5DT glove on my dominant hand and the Omni in my non-dominant hand. The Data Glove works well for rough positioning and the Omni for the fine positioning. In this configuration, it was hard to get precise with my non-dominant hand" |
| 102148 | "I would tend to want to handle insertion with my dominant hand and would need to wrangle objects into the correct spaces to make that happen" |

task. In general, participants performed equally well through all five of the treatment conditions. However, in answer to the open-ended question, several participants indicated that having one glove and one haptic device was their favored configuration.

While not quantitatively measured, anecdotal observation of the participants indicated that the participants who performed the task in the shortest time were those that used both hands at the same time. The task given to the participants did not require two-handed manipulation. Perhaps a redesigned task which includes a gravity force and therefore requires the use of both hands may have produced different results across treatments. González-Badillo et al. (2012) found that including the weight of the virtual objects affects the task completion time in bimanual virtual assembly tasks. Another interesting aspect to explore would be to examine the number of movements needed to assemble the part.

There is a marked challenge in comparing haptic and non-haptic devices that differ in a variety of different factors (workspace, accuracy, force feedback , etc.). These differences result in potential confounding variables that can be difficult to account for. The additional testing of other configurations of devices would be beneficial in understanding when it is appropriate to use certain configurations of devices. Additionally, it would be helpful to identify the factors that contribute to task difficulty. The lack of torsion feedback for the Phantom Omni could potentially have been a factor in task performance as well as participant device preference. Future testing could compare the 3DOF versus torsional force utilized during different types of assemblies by users.

The significant differences in task time between males and females is an interesting result. It could be due to the reported difference in computer experience between the genders or perhaps a difference in spatial ability. Gender differences in spatial ability has been identified in other studies. Men have been shown to score higher on spatial tests relative to women (Linn and Petersen 1985). The importance of spatial ability in virtual assembly needs further investigation.

There appears to be an incongruity between the time it took participants to put together the objects in the different treatments and their self-reported preference for hardware configurations. One would think that performance would be related to preference; however, participants seemed to predominantly prefer haptics and felt that it was quite beneficial in helping them assemble the objects. Why is it then that participants had a clear preference irrespective of their performance? One possible explanation is the misinformation effect.

The misinformation effect says that presenting information, whether correct or incorrect, between the encoding of an event and recall can influence the memory of the event and impair the ability to accurately recall details about it (Loftus and Hoffman 1989; Loftus et al. 1978). In this case, there was no purposeful misinformation provided to confuse participants but the constant changing of device configurations through switching hands and hardware may have been confusing to participants. Participants were told at the start of each task which device configuration they would be using; however, this misinformation effect may have influenced their memory of the treatments. In addition, because most participants did not have prior experience with virtual reality or haptic devices, the novelty of the devices could have played a role in determining what they remembered.

## 5 Conclusion and future work

In an effort to evaluate the usefulness of five bimanual virtual assembly device configurations, a user study was performed. The results indicated that there were no significant differences in task completion times for the five bimanual configurations tested and that male participants had faster completion times than female participants. This may be attributed to a difference in computer experience between genders. Participants also indicated that haptic feedback was beneficial in their ability to assemble virtual products and the majority of the participants preferred using at least one haptic device.

There are additional variables that were not included in this study that we would like to examine in future work. In the present study, performance was measured by the time taken to perform the task. However, the motivation for the study was to evaluate a bimanual interface that includes haptics yet expands the ability to manipulate objects to an area larger than that of the haptic device. In addition, we wanted to give participants the flexibility to perform the task in their own desired way. To better evaluate the performance, it would be beneficial to save the location and orientation of the objects to determine how users are orienting and positioning the objects prior to insertion to see whether there are differences in the way they assemble parts when using different hardware configurations as well as how much of the workspace of the glove participants used. This additional information could be used in comparing the potential benefits of the expanded workspace enabled through glove interaction as compared to a haptic device with a smaller workspace. Another possible improvement would be to force the assembly process as a bimanual task that would require use of both hands at the same time. This might be a good configuration when addressing performance characteristics of the devices. The downside of forcing the user to use both hands like that is that the experience becomes less natural and may not necessarily mimic real-world assembly.

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## References

Balakrishnan R, Hinckley K (2000) Symmetric bimanual interaction. In: CHI '00: proceedings of the SIGCHI conference on human factors in computing systems, ACM, New York, NY, USA, pp 33–40. doi:10.1145/332040.332404

Balakrishnan R, Kurtenbach G (1999) Exploring bimanual camera control and object manipulation in 3D graphics interfaces. In: CHI '99: proceedings of the SIGCHI conference on human factors in computing systems, ACM, New York, NY, USA, pp 56–62. doi:10.1145/302979.302991

Bowman DA, Hodges LF (1997) An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In: SI3D '97: proceedings of the 1997 symposium on Interactive 3D graphics, ACM, New York, NY, USA, pp 35–ff. doi:10.1145/253284.253301

Crossan A, Brewster S (2006) Two-handed navigation in a haptic virtual environment. In: CHI '06 extended abstracts on human factors in computing systems, ACM, New York, NY, USA, pp 676–681. doi:10.1145/1125451.1125589

Dominjon L, Lécuyer A, Burkhardt JM, Andrade-Barroso G, Richir S (2005) The "bubble" technique: interacting with large virtual environments using haptic devices with limited workspace. In: First joint eurohaptics conference and symposium on haptic interfaces for virtual environment, Pisa, Italy, pp 639–640. doi:10.1109/WHC.2005.126

Fiorentino M, Uva A, Fabiano MD, Monno G (2010) Improving bimanual 3D input in cad modelling by part rotation optimisation. Comput Aided Des 42(5):462–470. doi:10.1016/j.cad.2008.12.002

Fischer AA, Vance JM (2003) Phantom haptic device implemented in a projection screen virtual environment. In: IPT/EGVE workshop proceedings. Zurich, Switzerland, pp 225–230

Giachritsis C, Barrio J, Ferre M, Wing A, Ortego J (2009) Evaluation of weight perception during unimanual and bimanual manipulation of virtual objects. In: World haptics 2009 - third joint EuroHaptics conference and symposium on Haptic interfaces for virtual environment and teleoperator systems, Salt Lake City, UT, pp 629–634

González-Badillo G, Medellín-Castillo H, Fletcher C, Lim T, Ritchie J, Garbaya S (2012) Effect of weight perception on human performance in a haptic-enabled virtual assembly platform. In: 37th International MATADOR conference, Manchester, England, pp 231–234. doi:10.1007/978-1-4471-4480-9

Guiard Y (1987) Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. J Motor Behav 19(4):486–517

Gunn C (2006) Collaborative virtual sculpting with haptic feedback. Virtual Real 10:73–83. doi:10.1007/s10055-006-0044-4. http://portal.acm.org/citation.cfm?id=1164941.1164943

Hinckley K, Pausch R, Proffitt D, Patten J, Kassell N (1997) Cooperative bimanual action. In: CHI '97: proceedings of the SIGCHI conference on human factors in computing systems, ACM, pp 27–34. doi:10.1145/258549.258571

Hinckley K, Pausch R, Proffitt D, Kassell NF (1998) Two-handed virtual manipulation. ACM Trans Comput Hum Interact 5:260–302

Isshiki M, Sezaki T, Akahane K, Hashimoto N, Sato M (2008) A proposal of a clutch mechanism for 6dof haptic devices. In: Proceedings of the 18th international conference on artificial reality and telexistence, Yokohama, Japan, pp 57–63

Kron A, Schmidt G, Petzold B, Zah M, Hinterseer P, Steinbach E (2004) Disposal of explosive ordnances by use of a bimanual haptic telepresence system. IEEE Int Conf Robot Autom 2:1968–1973. doi:10.1109/ROBOT.2004.1308112

Linn MC, Petersen AC (1985) Emergence and characterization of sex differences in spatial ability: a meta-analysis. Child Dev 56(6):1479–1498. http://www.jstor.org/stable/1130467

Loftus EF, Hoffman HG (1989) Misinformation and memory: the creation of new memories. J Exp Psychol Gen 118(1):100–104. http://psycnet.apa.org/psycinfo/1989-24881-001

Loftus EF, Miller DG, Burns HJ (1978) Semantic integration of verbal information into a visual memory. J Exp Psychol Hum Learn Memory 4(1):19–31. http://psycnet.apa.org/journals/xlm/4/1/19/

Marteniuk RG, MacKenzie CL, Baba DM (1984) Bimanual movement control: information processing and interaction effects. Q J Exp Psychol 36(2):335–365

McNeely WA, Puterbaugh KD, Troy JJ (1999) Six degree-of-freedom haptic rendering using voxel sampling. In: Proceedings of the 26th annual conference on computer graphics and interactive techniques—SIGGRAPH '99, ACM Press, New York, New York, USA, pp 401–408. doi:10.1145/311535.311600. http://portal.acm.org/citation.cfm?doid=311535.311600

OpenSceneGraph (2013) Openscenegraph. http://www.openscenegraph.org

Owen R, Kurtenbach G, Fitzmaurice G, Baudel T, Buxton B (2005) When it gets more difficult, use both hands: exploring bimanual curve manipulation. In: In GI 2005 proceedings, pp 17–24

Pavlik RA, Vance JM (2011a) Expanding haptic workspace for coupled-object manipulation. In: ASME 2011 world conference on innovative virtual reality, ASME, Milan, Italy. doi:10.1115/WINVR2011-5585

Pavlik RA, Vance JM (2011b) VR JuggLua: a framework for VR applications combining Lua, OpenSceneGraph, and VR Juggler. In: Workshop on software engineering and architectures for realtime interactive systems (SEARIS) in IEEE virtual reality, Singapore

Pavlik RA, Vance JM (2015) Interacting with grasped objects in expanded haptic workspaces using the bubble technique. ASME J Comput Inf Sci Eng 1–7. doi:10.1115/1.4031826

Peters M (1985) Constraints in the performance of bimanual tasks and their expression in unskilled and skilled subjects. Q J Exp Psychol 37(2):171–196

Poupyrev I, Ichikawa T (1999) Manipulating objects in virtual worlds: categorization and empirical evaluation of interaction techniques. J Vis Lang Comput 10(1):19–35. doi:10.1006/jvlc.1998.0112

Shaw C, Green M (1994) Two-handed polygonal surface design. In: Proceedings of UIST 94. Marina del Rey, CA, pp 205–212

Talvas A, Marchal M, Cirio G, Lécuyer A (2013) 3D interaction techniques for bimanual haptics in virtual environments. In: Ferre GM (ed) Multi-finger haptic interaction. Springer series on touch and haptic systems, chap 3, pp 31–53

Vélaz Y, Lozano-Rodero A, Suescun A, Gutiérrez T (2014) Natural and hybrid bimanual interaction for virtual assembly tasks. Virtual Real J 18(3):161–171. http://link.springer.com/article/10.1007

VRJuggler (2013) Vrjuggler. http://vrjuggler.org

Vyawahare VS, **Stone** RT (2012) Asymmetric interface and interactions for bimanual virtual assembly with haptics. In: Proceedings of the ASME 2012 international design engineering technical conferences and computers and information in engineering conference. ASME, Chicago, Illinois, pp 1–9

Vyawahare VS, Stone RT (2013) Evaluation of bimanual stretched-string single object manipulation for virtual assembly with haptics. In: Proceedings of the ASME 2013 international design engineering technical conferences and computers and information in engineering conference (IDETC/CIE 2013). ASME, Portland, Oregon, pp 1–10

Vyawahare VS, Vance JM (2009) Human centered multimodal 3D user interface for desktop VR assembly. In: Proceedings of the emerging technologies conference 2009, ETC