Effects on Performance of Analytical Tools for Visually Demanding Tasks through Direct and Indirect Touch Interaction in an Immersive Visualization

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Abstract

In this paper, we present an investigation on the performance effects of analytical tools through visual and non-visual interaction in an immersive visualization. We explored two types of touch-based input device (with a display screen as direct and without a display screen as indirect), and compared these two touch-based input devices with a 6-degrees of freedom (DOF) tracked input device and a 2DOF input device, where a user could interact in 6DOF spatial context but the degrees of freedom were constrained. The results revealed that for visually demanding tasks, touch input is comparable to 6DOF, however it is important to use physical means to constrain degrees of freedom to retain performance levels using analytical tools involving selection. Furthermore results revealed that precision can be negatively affected by the design of the direct touch interface. Our results will have implications on touch-based interface design as well as design considerations when reducing degrees of freedom control.

Keywords: Touch; Direct; Indirect; Immersive Visualization; Input Devices; Interaction; Degrees of Freedom; Analytical Tools; Evaluation; Selection

1. Introduction

An immersive visualization environment is one where the user can feel more a part of the environment, influencing as many of the senses as possible. There are advantages and challenges to exploring visualizations using immersive displays (Figure 1). One challenge includes users' control of visual analytics tools. These options are usually displayed as 3-Dimmensional (3D) widgets in the environment, but continue to function as 2D [2,6]. Often 3+ Degree of Freedom (DOF) interaction in an immersive context system allows user to do translation and orientation input of the x, y and z axes and people prefer to do 2D selection in 3D widgets where the function menu items displayed in [4,7], since acquiring the perception of the depth of the widgets is difficult while selecting a 3D menu item in an visualization Although some of 3+ DOF input devices are appropriate for controlling the user's view, manipulating the data and performing tasks, commonly found in traditional virtual environments, they may be not suitable for the advanced analytic tools with high number of menus and controlling points. Hence, using a 3+ DOF input device in this context may make the user's task more difficult, uncomfortable, and cause higher levels of cognitive and physical fatigue. These added demands may hinder scientific discovery and interfere with user's attention, therefore, there is a need to figure out the interaction solution as well as determine if reducing degrees of freedom improves performance in this context.

We propose to use a mobile touch-based display device as a portable, effective and scalable interaction device in the immersive visualization environment. We determined the differences among using direct touch, with a display, and indirect touch, without a display. Some previous researches have shown that a tablet can enhance the user experience in a VR environment by providing mobility and reducing arm fatigue [2, 6] and some other studies indicate that tablets could be a suitable interaction device for visualization applications [14], but little research has been conducted to fully explore its benefits in the context of immersive visualization system comparing direct verses indirect touch, as well as compare it with other forms of degrees-of-freedom reduction and 6-DOF input.

Hence, the goals of our research are to determine the differences among direct and indirect touch, as well as compare those with an alternative method of constraining degrees of freedom. We chose an analytical tool that would involve selection and accuracy driven interaction. We also investigated two ways of abstracting the task, as a target-based task and a visually controlled task to determine whether context switching will impact the users' performance, since a not fully invested result in a research showed it has negative effects when screen flickering is an issue [9].

Our hypotheses were:
H1: Touch-based input enables better performance
H2: Touch-based input allows faster task completion
H3: Mobile touch-based input is most preferred
H4: Context Switching will have a negative impact on direct touch, or touch-based input with a display

2. Related Work

2.1. 6DOF interaction

Six degrees of freedom (6DOF) allows for translational input along the x, y, and z axes as well as rotational input around the x, y, and z axes [4]. For an immersive display with 6DOF, we need to account for the six aspects to the usability of a 6 DOF input device: speed, accuracy, ease of learning, fatigue, coordination, device persistence, and acquisition [17]. Previous research has shown that 6DOF interaction with a 2DOF device like a traditional mouse can be difficult, because of its DOF constraint and coordinate of motion problem [17]. Bowman, et al. has shown that buttons could be added to a 2DOF input device to increase the Degrees of Freedom for that device to provide a better performance [4].

The Wii-mote, a game controller by Nintendo, has become quite popular for VR interaction in recent years. Yang Wai Chow introduced the feasibility of using Wii-mote for 3D interaction [19]. A Head Mounted Display (HMD) system was used for interactions, but he neither conducted any usability studies nor assessed user-performance. Moreover, Yang's study is different from our research, especially his research only can track appropriate +/- 45 degree pitch and roll. Beatriz Sousa Santos et al. also studied a user's performance to compare the usability of a Wii-mote as an input device to visualize information and navigate in Google Earth using two different configurations- infrared and accelerometers [1]. In our study, we are using an optical tracking system to track the Wii-mote and gather 6DOF input data. We also collect user-experience and usability evaluation data from all the input devices. Furthermore, [1] didn't indicate whether Wii-mote is a preferred input device in a large immersive system.

2.2. Touch-based Interaction

In a 3D workspace, a user should have freedom of manipulating the object and be allowed the maximum menu-free screen possible. Tablet menu display can be beneficial for VE since a user gets the entire screen to work with and also the comfort of familiar 2D menus [9]. Tablet touch device combined with a large screen display can act as a stimulus to enhance the quality of visual effects [8]. One study investigates the use of a Wacom tablet, a touch-pad like tablet, for 3D selection tasks in [15]. These results have potential for visualizations, but little focused on investigating interaction with 2D widgets in the context of visualization where complexity is high, attention is divided, and consistency is needed. Our focus is primarily investigating the performance with visual analytic tools for immersive visualizations.

Steinicke et al. discussed that multi-touch interfaces can have favorable results for 3D manipulation tasks (selection, rotation, translation, scaling) [7]. Handheld touch tablets with displays and ones without displays have been used in previous studies. The ones without displays have been used in similar ways to a touchpad on a laptop. Wacom tablet, a touch-pad like tablet has been used for 3D selection tasks in an earlier study [18]. However [9,7,18] only focused on one type of device, rather than the differences among constraint and display type. Our research investigates these additional aspects.

2.3. 2D Menus in Touch displays

Clifton Forlines et al. used a WIMP based menu control on a tablet that constrained the movement in a 2D plane that enhanced the interaction performance than in free-space interaction [6]. A research conducted by Bowman et al. showed that using a pen and tablet device for 2D menu control in a virtual environment caused less arm and hand strain compared to ray-casting technique for selection from floating menus, GUI [2]. Research conducted by Jian Chen et al. found that tablet touch device combined with a large screen display for virtual environment can act as a stimulus to enhance the quality of visual effects by providing mobility to users while interacting with naturalistic view of data [8]. However did not investigate how this would compare between direct and indirect, only indirect touch. Our study aimed to investigate these additional aspects.

Figure 1. Immersive Display

3. Experimental Study

3.1. Apparatus

In this study, we used 1 immersive display and 4 input types. We used a CAVE Automated virtual environment (CAVE) system as our experimental environment (see Figure 1) at the Idaho National Laboratory (INL) [3]. This CAVE system had 4 display screens, which were front, left, right and bottom screens. An optical tracking system was used on the top of the CAVE. The input devices included a LG G-Slate android tablet; Wii-mote; Wacom Bamboo touch-pad and Gyration Air-mouse (see Figure 2). Wii-mote with tracking balls was used as 6DOF interaction device in combination with the Ray-casting technique [2] as our control method. Wacom Bamboo touch-pad restricted hand movements along the x and y axes for 2DOF input. We labeled these 3 buttons to indicate their functions, so the user can focus on the tasks rather than remembering their functions. Gyration Air-mouse can be used freely in the air without touching any flat surface. It allowed user to do 6DOF motions, but constrained the input to 2DOF along x and y axes. The Air-mouse also had buttons for a user to adjust the cursor on the screen and triggering the menu. We used VRUI VR toolkit for visualization in the immersive environment. The menu and visual analytical tools displayed on the tablets were the same as displayed in the immersive visualization system to provide the same interfaces to users. We developed an android application which simulates the menus and visual analytical tools and deployed it on the G-Slate tablets. Devices were wireless connected to the system by Bluetooth. We used VRPN to communicate tracking system with the visualization system. We custom implemented the logging function and the communication between devices and the system.

Figure 2. Input devices: a) G-Slate android tablet; b) Wii-mote: c) Wacom touch-pad; d) Air-mouse

3.2. User Types

Participants in our study included students and employees aging from 18 to 65 at the University of Wyoming and INL. Participants had 20/20 vision or corrected to 20/20 vision and fully used of at least one hand. There were two types of participants: novice and expert. Novices were participants who had not familiar with application aspects. Experts were those participants who were familiar with the immersive display system for at least 1 year and who also had frequently used the application and traditional 6DOF input devices.

3.3. Design

3D interaction tasks can be categorized into 3 types: 6DOF manipulation, navigation and menu/widget operation. Previous research has investigated 6DOF manipulation, such as rotation or translation, and navigation [1], but few have looked at the performance among analytical tools. Select and filter have been identified as most common analytical tasks, therefore we used this type of task in our evaluation. Furthermore, we abstracted the task as a target based task to gain accurate performance data but also used a visual based task in order to make the task more realistic for scientists' usage and evaluate context switching.

3.4. Task

A 1D transfer function provided several analytical and visualization tools, which played important roles in direct volume rendering, to users. It assigns the visualization of volumetric dataset based on a single scalar quantity to optical properties such as color and opacity [9, 11]. In our study, all participants had to perform a pre-designed 1D Transfer function task by using every device. In this 1D Transfer function task, we create a randomly appeared red rectangle in the histogram part. The participant needed to select and move the control point to overlap it. When the user thought he/she had overlapped the red rectangle properly, then he/she could start a new trial. After pressing the next trial button, the previous red rectangle would disappear and a new red target will appear randomly in the histogram, while the control point position wouldn't change. Hence, the participants wouldn't pre-know their new mission before starting a new trial, which was more likely close to our real tasks. The modified 1D transfer function interface displayed in the visualization system could be seen in Figure 3 and Figure 4 showed the interface on the G-Slate.

Figure 3. Task widget displayed in CAVE

Figure 4. Task widget displayed on Touch Display

There were totally 10 trials in this task, 5 non-visual trials and 5 visual trials. The order of visual trials and non-visual trials was random. For the non-visual trials, participants needed to select and move the control point in the histogram to the randomly appeared red rectangle position and try to overlap it without paying too much attention on the visualization change. In these trials we could study the performance if the user pre-knew what value needed to be set or he/she had a target in mind by using an analytical tool. For the visual trials, the participant had to look at the desired visualization displayed on the slides first, then manipulated the control point to a position to change the visualization, in order to match the volume to the desired visualization on the slides. To get accurate logging data, the participant would decide when to start the next trial. In visual trials, we could study the performance if the participant didn't pre-know the value needed to be set by using analytical tools. In this way, we tried to get a full evaluation of the performances.

3.5. Procedure

At the beginning of the study, we would briefly explain our study to the participants and then asked them to read and sign a consent form that described the purpose of the study, its benefits and potential harms. Then participants were asked to complete the pre-experimental tests, such as spatial test and Stereo test. In these tests, we would make sure they have ability to see 3D objects and feel comfortable in a 3D immersive environment. Then participants would respond to pre-experimental measures. Each participant would be assigned with a task and a random order of devices to avoid producing any ordering confounds and to balance the affection of the order of devices. Participants were then introduced the display type and input device they were going to use. They also were given time to become familiar with the 3D glasses and the facilitator made sure that users were comfortable wearing it. At any point of time during the study, if they felt uncomfortable or tired, participants could take a break or choose to discontinue the study without any penalty. After familiar with the system and devices, participants were given two test trials to learn how to actually use the current input device. Our pilot study showed that, two test trials were very necessary, because it made the participant feel more comfortable with the device and system, and relax user's tension mood which would help us get accurate data. Once training trials were completed, participants completed test trails. After completing all of 10 trials by using one device, the participant could take a short break and completed a performance questionnaire, then repeat with the next device condition. After finishing the task by using all of the devices, participant needed to respond to post-performance questionnaires and a debriefing interview. Then, they were thanked for their participation.

3.6. Measures

3.6.1. Pre-experimental measures

We collected demographic information of the participants and the extent of their daily usage of computers. Their experiences of viewing 2D and 3D images and using input device to interact with an immersive environment were also asked. We also asked them questions related to their experience of using scientific data visualization applications.

3.6.2. Performance measures

During the tasks, our customized application automatically logged device type which was using, trial type, trial number, completion time of each trial and control point position, randomly appeared target position, the number of key strokes, the number of missing selecting the control point and etc. Additionally, during the task period, 2 facilitators took observation notes of the participants' behavior, attitude and words. After completing all 10 trials in a task by using a device, we collected information on workload using the NASA-TLX workload assessment questionnaire. It consisted of questions related to mental, physical and temporal workload, own performance, frustration and effort to gather user experience with each device [15]. Participant was also asked to complete a questionnaire after taking the NASA-TLX, to assess their performance based on self-perception of accuracy, learnability and comfort.

3.7. Results

A repeated measures ANOVA was used to analyze the data, using p=0.05 to indicate significance. When Mauchly's Test of Sphericity was significant, we used Greenhouse-Geisser for correction.

3.7.1. Participants

A total of 18 participants (3 experts, 15 novices) participated in this study (age 18-56, M=30, SD=10.90). Participants included students, faculty, administrator staff, technical staff, and scientists. The means of pre-experimental measures are: experience with touch-based devices (M=5.14, SD=1.57; experience with 3d/stereoscopic viewing (M=3.45, SD=1.62); Expert users' visualization experience was high (M=7.0, SD=0.0) and low with novice users (M=1.75, SD= 0.98). All participants met the minimum inclusion criterion.

3.7.2. Performance Error: Control Point Selection

3.7.2.1. Target Distance Errors

Target distances were calculated from the final positioning of the control point to the target position. Since there was no specific position-based target for visual trials, those were omitted from this analysis. All of the conditions used the same scale for the widget except for touch with a display. The reported values for the touch with the display were converted into the display space of the other conditions given the widget size, display resolution, and input acuity. One participant's data was removed from the analysis because their data revealed that across all device conditions he/she was performing the task without care or effort, furthermore left before completing the last task.

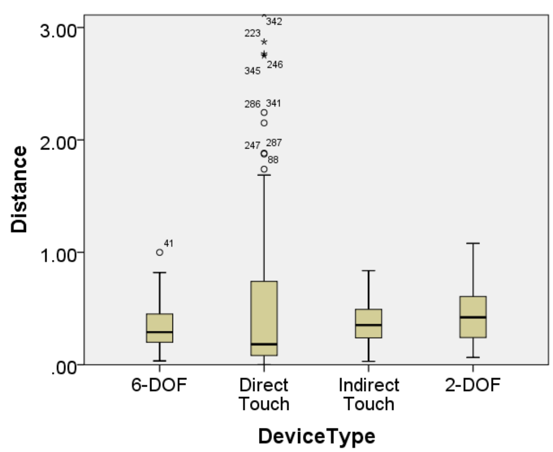

Figure 5. Target Distance Error among Input.

3.7.2.2. Selection Misses and Accidental Creation of Control Points

Table 1. Target distance error among input

	Mean	Standard Deviation
Touch with a display	*0.57*	*0.84*
Touch without a display	*1.00*	*0.84*
6DOF	*0.84*	*0.82*
2DOF	2.26	1.64
F(3,275)=3.35, p = 0.019, n^2 = 0.36		

**Italic marked devices have better performance than the normal marked device*

There was a significant difference of distance errors among device type, $F(3,275)=3.35$, $p=0.019$, $n^2=0.36$, where a LSD post-hoc test revealed that touch with a display (M=0.57, SD=0.84), 6DOF (M=0.84, SD=0.82), and touch without a display (M=1.00, SD=0.84), all had had significantly less distance error than a 2DOF (M=2.26, SD=1.64) (Figure 5 and Table 1). The former three were not significantly different from each other. Note that the high standard deviation for the 2DOF can be explained by one signal trial, not included in the figure for readability, which has a distance error = 11.81.

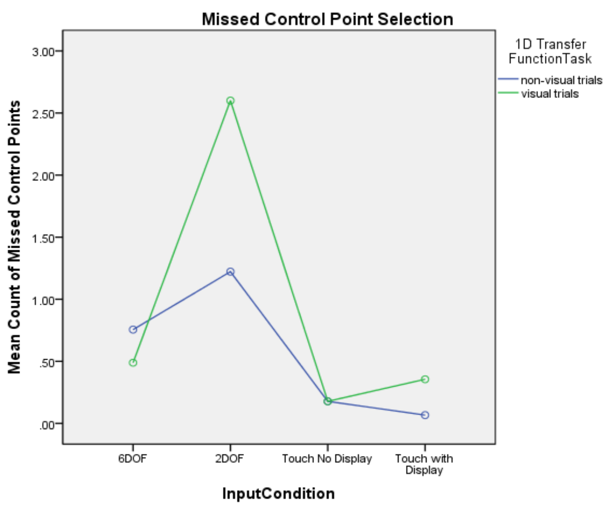

Figure 6. Missed Control Point Selection by Input and Task Type.

Table 2. Missed control points

	Mean	Standard Deviation
Touch with a display	*0.21*	*0.22*
Touch without a display	*0.18*	*0.58*
6DOF	0.62	1.44
2DOF	1.9	3.28
$F(3,132) = 15.39$, $p<0.001$, $n^2 = 0.26$		

**Italic marked devices have better performance than the normal marked devices*

What is interesting in this analysis is the variability reported for the touch with a display. This result shows that precision is low for the direct touch condition. Precision is how consistently the same result is produced compared with accuracy which is how correct is the result. Through observation, we found that participants had a difficult time discerning exactly where the control point lined up with the target. This led to the lower precision. We interpret these results attributing to the physical differences among participants, the visual feedback coordination with direct input and widget design.

The touch conditions, with a display (M=0.21, SD= 0.22) and without a display (M=0.18, SD= 0.58) produced a significantly lower number of missed control points than 2DOF (M=1.9, SD=3.28) and 6DOF (M=0.62, SD= 1.44) input types, $F(3,132)= 15.39$, $p<0.001$, $n^2=0.26$ (Figure 6 and Table 2). There was not a significant difference among task type. The touch conditions, without a display (M=0.07, SD=0.25) and with a display (M=0.00, SD=0.00), produced a significantly lower number of accidental creation of control points than the 2DOF (M=.86, SD= 1.87) and 6DOF (M=0.12, SD=0.39) input conditions, $F(3,132)= 12.62$, $p=0.001$, $n^2=0.22$. There was a significant difference among task type for accidental creation of control points, $F(1,132)=5.40$, $p=0.03$, $n^2=0.11$. A higher number of attempts to create new control points resulted for the visual tasks than the non-visual tasks.

Touch without a display (M=1.71, SD=1.62) resulted in significantly lower presses than touch with a display, $F(3,132)=3.87$, $p=0.02$, $n^2=0.08$. The visual task produced significantly more button presses than non-visual tasks, $F(1,132)=27.23$, $p<0.001$, $n^2=0.38$.

3.7.3. Cognitive and Physical Fatigue

A NASA TLX Workload and other comfort and fatigue measures were analyzed by repeated-measures ANOVA. The 2DOF (M=48.07, SD= 29.21) and 6DOF (M=49.26, SD= 23.10) produced significantly more overall workload than touch with a display (M=26.72, SD=24.08) and touch without a display (M=25.44, SD=31.09), $F(3,51)=5.71$, $p=0.002$, $n^2=0.25$. Further analysis showed mental and physical demand were the main contributing factors. A repeated measures ANOVA found that participants using the modified 6DOF and touch without a display devices felt that they had to concentrate harder than using other 2 devices, $F(3,72) = 3.47$, $p = 0.02$ and $n^2 = 0.13$, yet still less than average (M = 4.16, SD = 1.60). Additionally, the touch with a display produced the lowest ratings (M = 3.32, SD = 1.51) signifying that cognitive workload was minimal for this condition. From the subjective comments, the 6DOF and constrained 6DOF input conditions produced the most arm fatigue.

3.7.4. Completion Times and Learnability

No significant difference in completion times were found among the four input conditions, F<1. When asked about accuracy in the post-questionnaire, participants commented that touch provided the most accuracy and control. Participants in commented on the lack of precision and difficulty to control and maintain accuracy for 6DOF and 2DOF. Additionally there were no significant differences found among change in completion times, nor error rate, over time across the trials. This either can be interpreted that all devices were easy to learn to begin with or that there was not enough time where the devices were used to determine any improvement in learning how to complete the task. Further investigation would be needed to know for sure.

3.7.5. User Preferences

When asked which of the input conditions that was preferred most, touch with a display was ranked highest (8 out of 19), and then 6DOF (6 out of 19), touch without a display (4 out of 19) and 2DOF (0 out of 19). The reasons for touch were "most comfortable", "easy to navigate and get specific values", "easy to go where you want to reach", "easy to switch as not too much thinking required", "easy and accurate", and "most responsive and least time taking". The 2DOF condition was preferred least due to "too sensitive", "hard to hold and press buttons", and "not accurate". The most preferred configuration was to use the 6DOF for navigation and the touch-based input (with or without a display) for selection. When asked about readability and context switching, participants had no problems with reading widgets/menus or switching between displays. Participants reported touch input conditions were easier to control, and liked the display on the touch device. Participants reported that they were more tired and that the interface was less intuitive when using the 6DOF and 2DOF conditions.

When asked to categorize these devices to task types, most participants wanted to use the 6DOF device for navigating and use touch-based devices (with or without a display) for selection. When about asked readability and context switching, participants had no problems with reading widgets/menus and context switching was not an issue for all participants except one.

4. Discussion and Design Guidelines

Our results show that there are fewer errors for the mobile touch-based input for missed control point selection, addition of control points, and distance from intended selection. We accept our hypothesis H1. Our results found no significant differences in completion times; therefore we reject our hypothesis H2. If speed is a factor, a 6DOF device may be just as appropriate. From the fatigue and preference ratings, users prefer touch-based input due to the lower physical fatigue, and higher comfort and ease of use. Additionally less mental fatigue resulted, in spite of context switching. This will allow scientists to better concentrate on their tasks rather than the interface itself. As a result, accept our hypothesis H3.

The results on completion times can be interpreted that if context switching was present through the use of a display as compared with no display, it was not significant enough to delay completion of any task. However context switching plays a role in increasing errors for missed selection, however the difference between the two types of touch devices was not significant. As a result, we reject our hypothesis H4.

Across the performance results, we have found that it is not sufficient to reduce just DOF, but a physical constraint is needed for improved performance. Using mobile touch-based interaction will reduce mental and physical fatigue and increase comfort and accuracy, thereby facilitating analysis and discovery with easy transition from desktop to immersive display use. Surprisingly we found that context switching does not have a negative effect on interaction with complex widgets in an immersive visualization.

Furthermore, we found decreased precision for direct touch, or touch-based input with a display. Observations revealed that users had a difficult time discerning where they more accurately line up the control point with the target point. Design considerations could consider users' physical attributes, size and design of visual analytical tools, and visual feedback. The interface could measure the users' physical attributes through cameras and other acquisition methods, then adjust the interface accordingly. Additionally, feedback methods such as passive haptic response and shadowing methods could be used to improve performance on precision. Further investigation of these design considerations would need to be completed. Also, although the benefits for providing a direct touch interaction include offloading the visual tools onto the secondary display, mirror visual feedback on the immersive display could be investigated as well.

5. Summary, Conclusion and Future Work

We explored two types of touch-based input device (with a display screen as direct and without a display screen as indirect), and compared these two touch-based input devices with a 6-degrees of freedom (DOF) tracked input device and a 2DOF input device, where a user could interact in 6DOF spatial context but the degrees of freedom were constrained. The results revealed that for performance results from the touch interaction were comparable to that of the 6DOF device, and significantly less for 2DOF. This suggests that although previous research recommends to reduce degrees of freedom, our new finding shows that degrees of freedom should be reduced physically to retain performance levels. Results revealed that precision can be negatively affected by the design of the direct touch interface. Our results will have implications on touch-based interface design as well as design considerations when reducing degrees of freedom control. Although our evaluation used a volumetric visualization task, as primary interaction is select and filter, we believe our results will generalize to other similar tasks. In the future, we will investigate more complex analytical tools and design considerations for touch displays.

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