Virtual Reality Interfaces for Interacting with Three-Dimensional Graphs

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ABSTRACT

Today, virtual reality (VR) systems are widely available through low-cost devices such as Oculus Rift and HTC Vive. Although VR technology has so far been centered on entertainment, there is a growing interest from developers, technology companies, and consumers to evaluate it in a wider variety of contexts. This paper explores the effectiveness of visualizing and interacting with three-dimensional graphs in VR in comparison with the traditional approach. In particular, we present an empirical evaluation study for exploring and interacting with three-dimensional graphs using Oculus Rift and Leap Motion. We designed several interfaces exploiting the natural user interface in a VR environment and compared them with traditional mouse–keyboard and joypad configurations. Our evaluation suggests that, although these upcoming VR technologies are more challenging than more traditional ones, they facilitate user involvement during graph interaction and visualization tasks, given the enjoyable experience elicited when combining gesture-based interfaces and VR.

1. Introduction

Recent interest in social networks, software architectures, planning, and scheduling has led to the application of graph visualization and exploration to assist analysts with relevant visual cues to understand the intrinsic structure of data. The amount of these structured data is constantly growing, and graph visualizations are aimed at helping with graph comprehension by providing graphical views to reveal hidden structures and other interesting topological features.

There are a set of effective approaches to visualizing a graph in two-dimensional (2D) space. A standard means of addressing the problem of constructing an automatic visualization of graphs is graph drawing, which uses an algorithm. The goal is to derive an aesthetically pleasing picture that follows the layout convention of a given application domain. One bibliographic survey (Di Battista, Eades, Tamassia, & Tollis, 1994) has gathered hundreds of studies of such layout algorithms. However, humans have an inherent ability to understand representations of objects in three-dimensional (3D) space (Erra, Scanniello, & Capece, 2012).

3D graph visualization is a relatively new field. Having one extra dimension enables the visualization of complex systems, in which navigation techniques, graph structures, and interface solutions play major roles. In particular, with real-time 3D exploration and interaction, users can navigate a graph and observe it from different points of view, move one or more nodes, or group unimportant nodes into clusters to reduce information overloading. In this way, because the user can navigate more effectively, 3D graph visualization is intuitively understandable and provides further information about a graph’s hierarchical structure. Whether or not 3D can be beneficial for many information visualization tasks in general is still an open question (Brath, 2014; Erra & Scanniello, 2012; McIntire & Liggett, 2014), but 3D graph visualizations in particular have been shown to offer great benefits (Ware & Mitchell, 2005, 2008).

Today, the representation of 3D space is possible using virtual reality (VR). Although this technology was first developed in 1970, it has only recently become widely available, through low-cost devices such as Oculus Rift (Luckey, 2012) and HTC Vive (HTC and Valve Corporation, 2012). In a VR environment, the user’s location is the focal point of the scene, and there is freedom in the user’s viewing direction because the entire sphere of directionality around that point is available. Visibility of the scene from the perspective of the user’s location is vital. However, in most VR applications, user interaction is based on an input device such as keyboard, mouse, or joystick. These methods break the illusion that users are directly interacting with the virtual world because they are a non-intuitive way to interact with virtual objects. To address this problem, researchers have begun to explore gesture-based interaction with VR content by using contactless motion-sensing devices. These devices, such as Microsoft’s Kinect (Kinect, 2010) and Leap Motion (Buckwald & Holz, 2010), track the body and hands in physical space, enabling developers to design invisible interfaces, also called natural user interfaces. In this way, they can provide natural free-hand gestures that allow deeper immersion into the VR application.

Although several works have explored stereoscopic graph visualization (Alper, Hollerer, Kuchera-Morin, & Forbes, 2011; Ware & Mitchell, 2005, 2008), there have actually been very few empirical studies into the applicability of VR to the field of graph visualization and interaction (Kwon, Muelder, Lee, & Ma, 2016). One important aspect of graph interaction is that it enables users to make changes to a graph drawing based on the users' input. This is particularly useful when the graph is very large, because, on the one hand, it reduces the difficulty and the time it takes the user to understand the information represented by the graph, while on the other hand, it increases the amount of information that can be interpreted and understood by the user. In 2D space interaction, completing a generic action requires at least two steps: click a specific button that is located outside the region in which the graph is displayed, and then move the mouse cursor to the graph region for executing the action desired. This two-steps paradigm has a disadvantage: the user is forced to move in and out of the graph region repeatedly, thus limiting interactivity within the graph. These actions often occur in mutual exclusion because of the mechanism of the toolbar.

Interaction in 3D space within VR environments offers different challenges. Because users lose all sight of their hands within a VR device, traditional mouse and keyboard interaction is limited, and actions happen in the virtual environment without using a toolbar or a menu.

We evaluated interfaces for interacting with 3D graphs in VR compared with a classic approach based on 2D visualization. In particular, using a plug-in module designed for the open-source graph and network analysis software package, Gephi, we evaluated 3D graph interaction using VR and a liquid-crystal display (LCD) monitor in combination with keyboard/mouse, joypad, and Leap Motion input devices. Our aim was to address specific interaction challenges by taking advantage of the tracking capabilities of the head-mount display of a VR system, to determine what the user is looking at, use this information to identify focal points, aid the user in making selections, and provide instantaneous details of the selected data.

The remainder of the paper is structured as follows. Section 2 provides an overview of related work. Section 3 describes the tool we designed to perform the experiments; it addresses the solutions proposed for 3D real-time interaction and manipulation in graph visualization. Section 4 presents in detail the six configurations for 3D graph interaction using VR and an LCD monitor in combination with keyboard/mouse, joypad, and Leap Motion input devices. The experimental comparison of the six configurations is presented in Section 5, followed by the results in Section 6. We end with some final remarks and future directions for our research in Section 7.

2. Related works

VR and stereoscopic techniques have a long history of use in scientific visualization (Brooks, 1999; Bryson, 1996; Dam, Forsberg, Laidlaw, LaViola, & Simpson, 2000) and application to medical imaging data (Mirhosseini, Sun, Gurijala, Laha, & Kaufman, 2014), volume data (Hnel, Weyers, Hentschel, & Kuhlen, 2014), and geographic information system data (Bennett, Zielinski, & Kopper, 2014). Also multimodal interactions with computer-simulated worlds through visual, auditory, and haptic feedback have a long history (Burdea, Richard, & Coiffet, 1996). In particular, stereoscopy has been shown to be beneficial for some information visualization tasks (McIntire & Liggett, 2014). Notably, stereoscopy has been shown in multiple user studies to be effective for graph visualization tasks (Alper et al., 2011; Greffard, Picarougne, & Kuntz, 2014; Ware & Mitchell, 2005, 2008). In Kwon et al. (2016), the authors compared layout, rendering, and interaction methods for immersive virtual environments with traditional 2D graph visualization, and showed that traditional 2D graph visualization is ill suited for immersive environments.

The literature contains many graph visualization systems. These systems usually take a 3D layout and add depth cues (Ware & Mitchell, 2008, 2005) or take a standard 2D graph visualization and add a 3D stereoscopic extension (Alper et al., 2011). In either of these cases, the display is often a monitor, and not an immersive system. In Halpin, Zielinski, Brady, and Kelly (2008), the authors used an immersive system starting from a standard 2D layout and then used stereoscopy just for highlighting. Barahimi and Wismath (2014) used a standard 3D layout for VR.

Regarding the input–output devices used, graph visualization tools are mainly mouse-based. Few works have addressed free-hand gesture interaction. In Nancel, Wagner, Pietriga, Chapuis, and Mackay (2011a), the authors studied the effectiveness of free-hand gesture interaction for pan and zoom actions on very large displays. They showed that free-hand gesture interaction is less effective than traditional interaction (mouse-based) in high-precision contexts because of the low level of guidance. In non-high-precision contexts, free-hand gesture interaction has been investigated for medical image visualization and navigation (Gallo, Placitelli, & Ciampi, 2011; Ruppert, Reis, Amorim, De Moraes, & Da Silva, 2012). Other fields in which natural user interfaces have been explored are the domotic (De Carvalho Correia, De Miranda, & Hornung, 2013), the robotic (Bassily, Georgoulas, Guettler, Linner, & Bock, 2014), and the Computer Music (De Prisco, Malandrino, Zaccagnino, & Zaccagnino, 2016*b*).

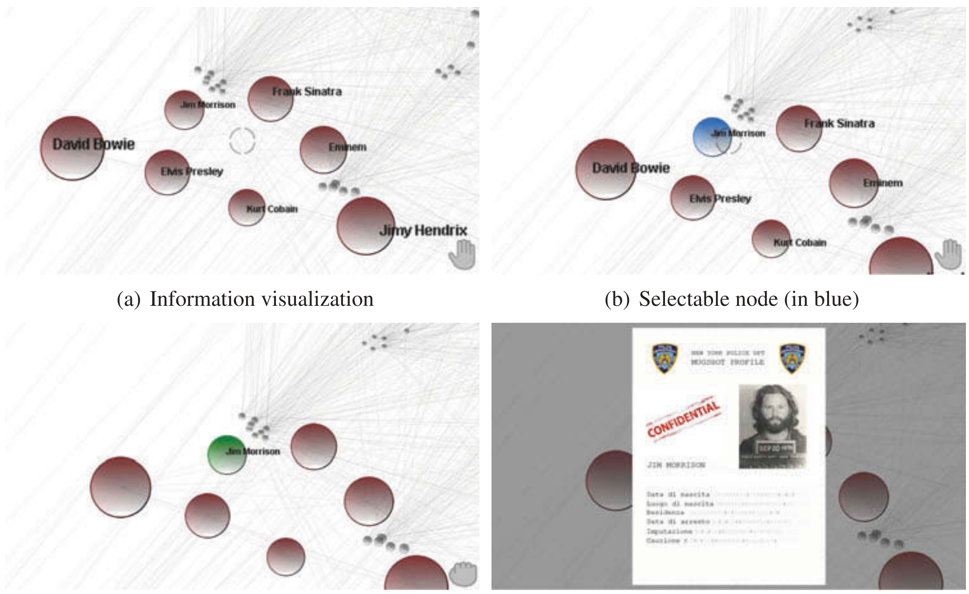
3. Interaction design

The tool we designed for our experimentation, named 3D Graph Explorer, is built on Gephi (Bastian, Heymann, & Jacomy, 2009), which is open-source software for exploring and manipulating networks. Gephi enables us to layout the networks, calculate metrics for the network nodes and clusters, and adjust the visual properties of the visualized network. Some of these built-in layout algorithms also enable us to arrange nodes in a 3D space, although visualization and interaction of the nodes is limited. In fact, the graph is arranged as a 3D model, and there is no way to rotate the viewpoint or move freely, because the standard visualization enables us to maintain only a fixed camera in a 2D space. The only feasible interactions in real time are to pan/zoom the graph from the toolbar or to move a node by using the drag and drop feature.

3D Graph Explorer is developed as a plug-in and exploits all the features of Gephi. In particular, it offers the following features: (i) visualization, exploration, and manipulation of graphs in 3D space; (ii) mouse/keyboard, joypad, and natural user interface support for interactive information-seeking; (iii) VR support for an immersive experience; (iv) utilization of Gephi features such as layout algorithms and graph filters.

To allow tasks to be performed on a 3D graph, the graph is explored by means of a resizable circular area positioned directly in front of the user. Nodes that fall within or that touch the border of the circular area are selectable. When nodes are selected, the user can obtain further information from them, or they can be resized, moved, or grouped in a cluster (see Figures 1 and 2).

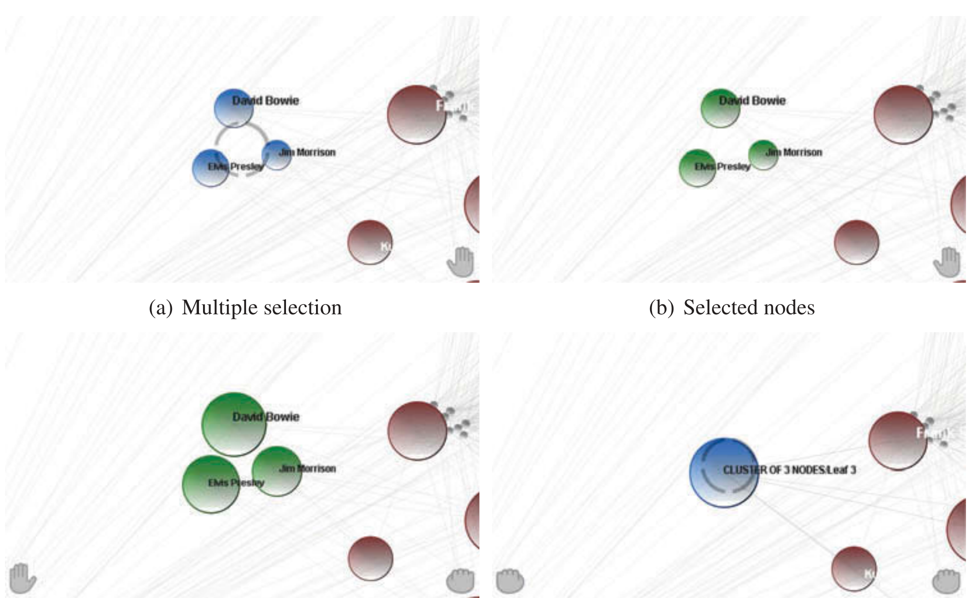
3D Graph Explorer allows users to explore freely and interact with a 3D visualization of a given graph obtained using a built-in layout algorithm of Gephi. Importantly, the graph is visualized in real time and users can navigate around it using a free-flying 3D camera. Users can move inside the graph and also move through all the nodes. This interaction



(a) Information visualization (b) Selectable node (in blue)

(c) Selected node (in green) (d) Details over a node

Figure 1. Exploring a graph. (a) Using the right open hand to navigate. (b) The circular area directly in front of the user is used to select nodes. (c) When the circular area is over a node, closing the hand selects that node. (d) Pointing the index finger of the left hand displays more detailed information on the node.



(a) Multiple selection (b) Selected nodes

(c) Nodes resizing (d) Nodes clustering (or grouping)

Figure 2. Multiple selection of nodes followed by resizing and clustering of the nodes. (a) Navigating to multiple nodes. (b) Selecting the nodes. (c) Resizing and (d) Clustering are performed using bimanual (two-handed) gestures. Holding the right hand still while moving the left hand up and down increases and decreases the size of the nodes. Closing and opening the left hand clusters and declusters the selected nodes. Clustered nodes are grouped and visualized as a single node. Clusters can be created by taking other clusters as input. Declustering returns the nodes to their original positions.

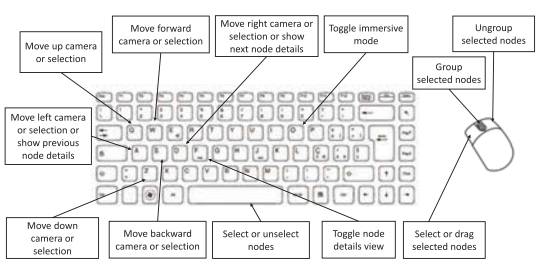
method of graph exploration in 3D space is based on computer games interaction, where control is mostly reduced to operating the standard input devices: mouse/keyboard and sometimes a joypad. The typical category of computer games that use this interaction are action games called first-person shooters. Our rationale is that over the course of the development of the games genre, this interaction method has been refined and is now generally fairly standardized. In addition, we identified in the design phase the requirement of fast interaction, hand–eye coordination, and reaction speeds, which are the primary model in action games (Rollings & Adams, 2003). This approach enables 3D human–computer interaction in which users perform tasks directly in the 3D spatial context (Bowman et al., 2008). For instance, moving, resizing, and grouping of nodes are performed directly in the 3D environment going over the classic graphical control elements where interactions between humans and machines occur. However, mouse/keyboard is not the only input device supported. In the following, we discuss in more detail the three main input devices supported: mouse/keyboard, joypad, and Leap Motion.

3.1. Mouse/Keyboard interaction

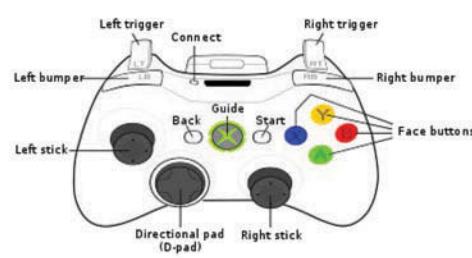
This configuration enables exploration using a combination of keyboard and mouse (see Figure 3a). The keyboard keys W, A, S, and D are used for movement forward, a side step (strafe) left, backward, and side step right, respectively. Moving the mouse rotates the viewing direction of the user (or camera). The circular area is fixed in the center of the screen and functions as described in Section 3. Keys Q and E are used to move the camera up and down, respectively. Lastly, the spacebar is used to select/unselect nodes. Mouse buttons are used in the following way: left button to drag and drop a node, middle button to group nodes, and right button to ungroup nodes.

Joypad interaction

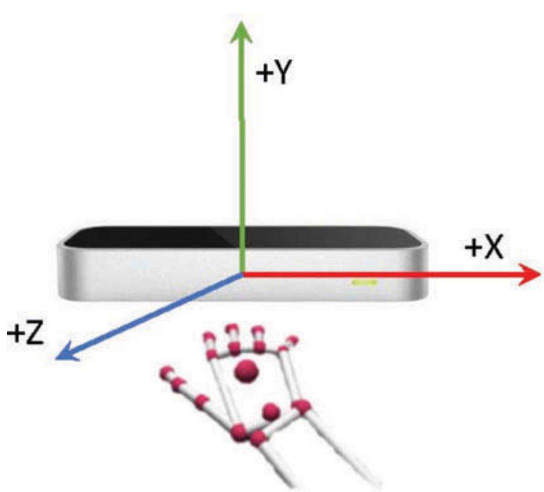
The joypad configuration is based on a compatible Microsoft Xbox 360 Controller (see Figure 3(b)). This has been a common input device for computer games for decades and can completely replace mouse/keyboard devices. In addition, it does not require a supporting plane, so it will be useful when used together with a VR headset. This controller has two analog sticks usually moved by the right and left thumbs. In our system, the right analog stick is used to move the camera up/down and right/left, and the left analog stick to move selected nodes left/right and forward/backward. Because these sticks provide a 2D input, we also use the buttons provided by the joypad. The standard joypad has eight primary buttons, which comprise four buttons usually pushed by the right thumb and four buttons in the front of the controller usually pushed by the right and left index fingers. Using two of the buttons in the front of the controller it is possible to move the camera up and down. The other four buttons are used to select/unselect, group, ungroup, and display details of



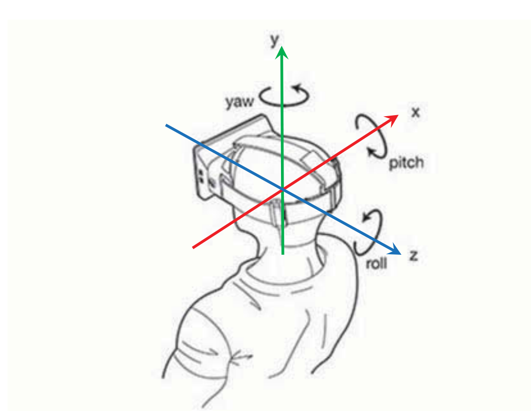
(a) Mouse/keyboard configuration



(b) Joypad configuration



(c) Leap Motion configuration



(d) Oculus configuration

Figure 3. The four input devices supported by the 3D Graph Explorer plug-in.

nodes on demand. Although this configuration can be quite complicated, it is well-known in the computer games industry for the exploration of 3D environments.

3.2. Natural gestures interaction

Leap Motion is a USB device released in 2013 by Leap Motion Inc (see Figure 3(c)). The device is capable of tracking all 10 fingers up to 1×10^{-3} of a millimeter (Buckwald & Holz, 2010). It has a wide 150 field of view and provides three types of spatial information: the location of fingers, the hand, and pen-like objects in Euclidean space; motion vectors for individual fingers and pen-like objects; and spherical representations of hand curvature. These features enable users to interact with their computer via hand gestures such as pinching or swiping. However, in 2013 it was shown that is not possible to achieve this theoretical accuracy conditions but a high precision (an overall average accuracy of 0.7 mm) with regard to gesture-based user interfaces (Weichert, Bachmann, Rudak, & Fisseler, 2013).

Designing interaction applications with Leap Motion must take into account several factors that could create a difficult and frustrating user experience. Two are the main factors of concern: the typology and quantity of gestures. Typology concerns the choice of gesture to perform an operation. In (Nancel, Wagner, Pietriga, Chapuis, & Mackay, 2011b), the authors studied interaction with large data sets using gestures such as mid-air and pan-and-zoom techniques. Their results suggest that bimanual (two-handed) interaction and linear gestures significantly improved performance. Another key aspect to take into account is "Gorilla Arm Syndrome," which causes strain on the arm and shoulder due to long periods of time spent with the hands up in front of the body while performing tasks (Shiratuddin & Wong, 2012). Therefore, the set must be designed to avoid the need for gestures that are too complex and that require high accuracy (Vatavu, 2017a). The second main factor, the quantity of gestures, concerns the number of gestures needed to perform tasks. This is important because the design must take into account the memory capacity of users. Experiments have shown (Jego, Paljic, & Fuchs, 2013) that the average number of gestures that a typical user can remember easily is three, and the researchers recommended that when designing an application this quantity of gestures is not exceeded.

Taking into account the above, we designed a set of user-friendly gestures that allow rapid interactions with 3D graphs in a virtual environment. Moreover, to support a better visual experience, the system shows visual feedback whenever it recognizes one or two hands and whether they are open or closed (see bottom right and left corners of Figures 1 and 2).

To explore a graph, the user has two modus operandi: linear and rotation mode. In both approaches, the user has an open hand, and Leap Motion tracks the palm posture and all the accompanying roll and pitch angles. That is, all data regarding the Cartesian coordinates and orientation of the user's palm are retrieved from the sensor. In the linear mode, the Cartesian coordinates enable the user to move the camera backward and forward (see Figure 4a). As we will discuss next, when coupled with a VR headset this approach is more comfortable to users. In the rotation mode, the Cartesian coordinates enable the user to roll and pitch the camera (see Figure 4(b) and 4(c)). When the user closes a hand, the system switches from exploring mode to manipulating mode. The user can move nodes selected within the circular area by performing the same operations used to move the camera. In addition, resizing, clustering, and displaying further information are enabled by using a set of bimanual gestures, as illustrated in Figure 5. Moreover, to avoid users experiencing "Gorilla Arm Syndrome," we defined a minimum arm extension in all directions and orientations. This means that an elbow-based gesture works as well as a shoulder-based gesture. All these gestures are defined so to be as intuitive as possible to most users, as discussed in Section 5.

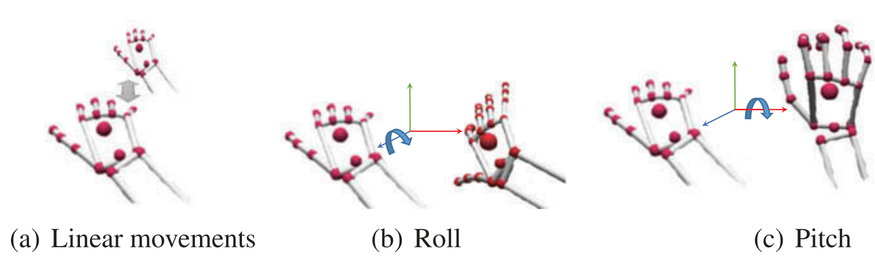


Figure 4. The two approaches to exploring a graph. The linear mode (a) enables the user to move the camera forward and backward. The rotation mode (b, c) enables the user to roll and pitch the camera.

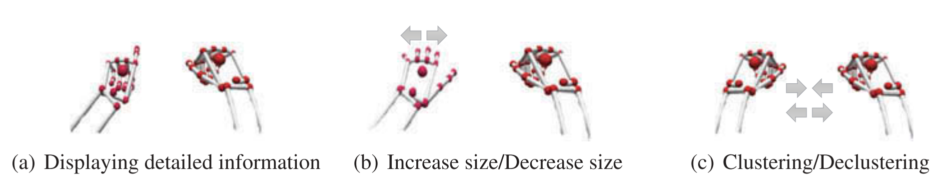


Figure 5. Bimanual gestures to manipulate a graph after selecting nodes with a closed hand. (a) Extending the index finger of the left hand displays additional information. (b) Holding one hand closed and moving the other hand up and down increases and decreases the size of the selected nodes. (c) Closing both hands and moving them toward each other clusters the selected nodes.

Virtual reality interaction

The VR headset supported is based on Oculus Rift, released in 2016 by Oculus VR and developed principally for gaming. The success of its Kickstarter campaign in 2012 and the first version of the device reinvigorated interest in VR experiences and paved the way for more new head-mounted displays. Oculus Rift Consumer Version 1 (Oculus CV1) provides an extended (110°) field of view, stereoscopic vision, and responsive head tracking. The device is easy to use, relatively inexpensive, and can be calibrated with a simple tool.

The advantages of integrating Oculus CV1 inside 3D Graph Explorer are twofold. First, users are offered an immersive exploration of graphs through stereoscopic vision. Second, it tracks head movements and changes the user's viewpoint in a realistic way. That is, the head-mount display is also used as an input device replacing the mouse in the mouse/keyboard configuration. Oculus CV1 is integrated inside 3D Graph Explorer in the following way. The user sitting in a chair switches the rendering from the LCD monitor to the VR headset. The device tracks head rotation and head tilt movements (see Figure 3d), which enables users who could be either standing or sitting to look around freely in the virtual environment in which the graph is rendered. Thanks to stereoscopic vision, users are totally immersed inside the graph and then has a better perception of its 3D representation. Because the device does not track the user's movement, other device input controls are required, such as Leap Motion. In particular, we use the linear mode discussed above. In this way, the user's head rotates the camera, while the user's hand moves the camera. This solution enables users to navigate through 3D space by flying and gesturing instead of using mouse and keyboard shortcuts.

4. Configurations

In this section, we describe the six configurations defined as combinations of input and output devices that we used in our evaluation (Table 1). Our rationale was to design a set of configurations based on using off-the-shelf devices and that does not require a complicated setup. In fact, all the configurations that we propose are designed to be used in a common desktop setup space where the user is sitting in front of the monitor and he can use the mouse/keyboard, joypad, and leap motion as input and a monitor or the Oculus Rift as output devices.

Three of our configurations were based on an LCD monitor output. The Traditional Configuration (*TRConf*) was composed of an LCD monitor and keyboard/mouse input devices. In this case, the user visualizes a 3D graph that is projected onto the 2D visual display and interacts with it using the keyboard and the mouse as described in Section 3. Because this configuration is the most commonly available among users, we consider it, in a certain sense, the ground truth configuration. The Gaming Configuration (*GameConf*) used a joypad as the input device, which is common among console game players but has also been used for tasks other than gaming (*Költringer et al., 2007) (Chiara, Santo, Erra, & Scarano, 2007). Lastly, the Natural User Interface Configuration (NUIConf) used the LCD monitor as output coupled with Leap Motion as input device. This configuration is the least common, but several works have investigated how Leap Motion is used for data visualization, such as (Adhikarla et al., 2014; Silva & Rodrigues, 2015).*

Our other three configurations were based on the head-mount display Oculus Rift as output (Chessa, Maiello, Borsari, & Bex, 2016). As discussed in Section 3, in this case the head motion tracking of Oculus Rift works as an input device that enables locomotion of the user in the virtual environment in the direction of the user's gaze. Here, the goal of the input devices is to provide the user with a means of moving around in 3D space and of interacting with the graph. However, there is currently a lot of debate in online communities about what is the best locomotion option inside a virtual environment, and so this is still an open problem. The first of these tested configurations was the Immersive Desktop Configuration (*ImmDeskConf*), which uses keyboard/mouse input devices. These input devices are the primary common approach to enable locomotion of users in a virtual environment. Although they are easy to understand, they can lead to motion sickness. The second configuration was Immersive Gaming Configuration (*ImmGameConf*), where the user controls the direction of movement using the gamepad's button. In Cardoso (2016), the authors compared joypad-based locomotion with several approaches and found that it is both faster and more comfortable. Lastly, the Virtual Reality Configuration (*VRConf*) is the most innovative because it uses only the hands for locomotion and for interaction, as described in Section 3. This configuration has the obvious advantage of not requiring users to hold a physical device, leaving their hands free to pick up physical objects, therefore enhancing participants' sense of presence in the virtual environment. To the best of our knowledge, few works have investigated a combination of these (Khundam, 2015; Lee, Wang, Y.-C., J.-W., & Valstar, 2015).

Table 1. Configurations as combinations of input and output devices.

Input/output	LCD monitor	Oculus rift
Keyboard/ mouse	Traditional Configuration (*TRConf*)	Immersive Desktop Configuration (*ImmDeskConf*)
Joypad	Gaming Configuration (*GameConf*)	Immersive Gaming Configuration (*ImmGameConf*)
Leap motion	Natural User Interface Configuration (*NUIConf*)	Virtual Reality Configuration *VRConf*

5. Evaluation study

In our evaluation study, we followed the standard human–computer interaction methodology (Lazar, Feng, & Hochheiser, 2010) that is commonly applied in various contexts (Al-Musawi, Ledesma, Nieminen, & Korhonen, 2016; Blake, Stapleton, Rodgers, & Howse, 2014; De Prisco et al., 2016a; De Prisco, Malandrino, Pirozzi, Zaccagnino, & Zaccagnino, 2017; Leon et al., 2012; Malandrino et al., 2015). Specifically, given the configurations described in Section 4, we wanted to answer the following questions:

- Which differences exist, when navigating structured data in a 3D environment, between innovative interaction modalities and traditional ones? Which configuration is the most effective?
- What are users' opinions about the usefulness, easiness, and playfulness of the proposed configurations? Can video-gaming abilities or demographic factors affect these metrics?
- What are the greatest factors influencing the adoption of innovative interaction modalities for 3D graph exploration?

5.1. Methodology

To find answers to the above questions, we conducted an evaluation study to analyze the use of different configurations in the context of 3D data visualization. We designed the study to compare innovative configurations, which exploit Leap Motion as input device and Oculus Rift as both input and output device, with more traditional configurations using conventional devices, namely joypad, keyboard, mouse, and LCD monitor. Technical details about the designed configurations and the interaction modalities have been described in Section 4. We compared these configurations to attempt to understand the differences between them when tested by participants.

We also studied the relationships of users' intentions to use these configurations with selected constructs from the technology acceptance model (TAM) (Davis, 1989), such as users' attitudes, perceived usefulness, ease of use, and playfulness.

The TAM is a widely used theoretical model to explain and/or predict potential users' behavioral intentions to access a technology or a new system. The TAM has been applied in numerous studies testing users' acceptance of information technology, for example, word processors (Davis, 1989), spreadsheet applications, email, web browsers, websites, and e-collaboration.

We extended the TAM model to analyze whether perceptions of playfulness (Moon & Kim, 2001) and attitudes toward using, in addition to ease of use and usefulness (Davis, 1989), appear to influence behavioral intention to use the defined configurations.

Procedure

The study was conducted in the ISISLab research laboratory at the University of Salerno, Italy. A personal computer was used, equipped with an i7, 3.40 GHz QuadCore CPU, a GeForce GTX 970 graphics card, and 8.00 GB of main memory. The input devices used for the experiments were a standard keyboard and mouse, a compatible Microsoft Xbox 360 Controller, and a Leap Motion device. The output device was a Full-HD 1920×1080 LCD monitor, while the supported VR headset was based on Oculus Rift. A detailed description of how the devices were used and combined has been presented in Section 4.

For the testing, we used a graph of Java dependencies (JPLD graph), modified to be rendered in a 3D environment.[1] The graph is composed of 1538 nodes and 8032 edges and was rendered at a fixed rate of 60 frames per second.

The study employed three phases (Figure 6), in which we carried out (i) a preliminary survey, (ii) a testing phase, and (iii) a summary survey, as defined and implemented in other contexts (Fish, Gargiulo, Malandrino, Pirozzi, & Scarano, 2016; Malandrino, Scarano, & Spinelli, 2013). All administered questionnaires are available online.[2]

In the first phase, we asked participants to fill out a preliminary survey questionnaire to collect (i) demographic information (i.e., gender, age, education level), (ii) information about information and communications technology (ICT) expertise, (iii) general attitudes toward video games, (iv) general familiarity and experience with both VR and graph theory. The 18 questions in this questionnaire (and listed in the Preliminary Survey Section) were: open-ended questions (questions with a "yes" or "no" dichotomous format), questions that asked participants to provide a preference up to 10 possible choices, and questions to be rated on a 5-point Likert scale with "strongly agree"/"strongly disagree" as verbal anchors.

In the testing phase, we asked participants to test a configuration by attempting to perform three different tasks. Participants were free to use and become familiar with the configuration within a training period of 10 minutes.

After that, participants were asked to complete the following three tasks:

- Task 1 (Searching): Given the JPLD graph, "try to find four black nodes within a fixed amount of time, and get close to them in order to visualize their labels."

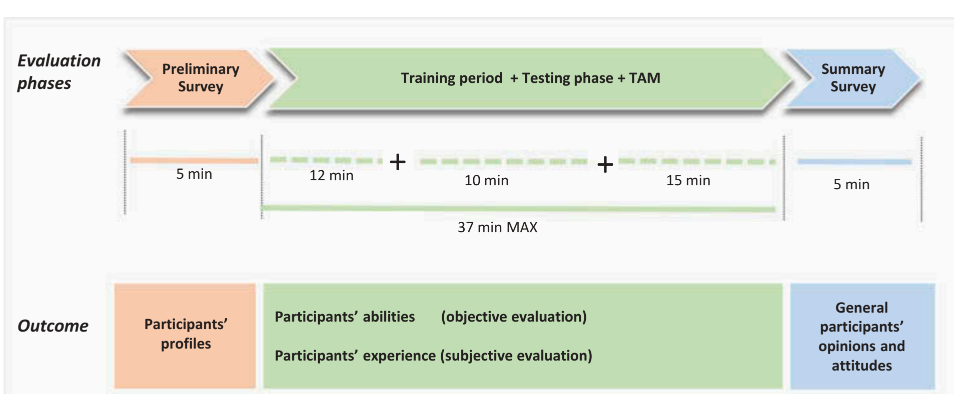


Figure 6. Timeline of a single user evaluation test.

[1]Java Programming Language Dependency graph (V. Batagelj), available to download from: http://www.isislab.it/delmal/NUI VR/JPLG.gexf.
[2]http://www.isislab.it/delmal/NUI VR/Questionnaire.pdf.

- Task 2 (Exploring): Given the JPLD graph, "explore it in order to select as many labels as possible, within a fixed amount of time."

- Task 3 (Clustering): Given the JPLD graph with two groups of gray nodes, "try to find and cluster them."

Task 1 was aimed at revealing the capacity of participants to orient themselves. Task 2 was aimed at testing their ability to move through a dense graph in order to obtain an idea of the structure of the graph. Note that labels were not counted by participants, but just selected. Conversely, the system counted the number of nodes approached by the participants. Moreover, labels were not selected (and therefore counted) multiple times, because after their selection by users, the system changes their color. In this way, users are informed that the nodes cannot be selected anymore. Finally, Task 3 was designed to test complex user interactions. As an example, the node grouping task requires as the first step the selection of the nodes themselves, in which case, for participants testing *VRConf*, a two-handed interaction was needed.

In all tasks, the participants were not aware of the maximum time allowed (5 minutes for Tasks 1 and 3, and 2 minutes for Task 2). This allowed us to assess the degree of the user's involvement without provoking anxiety during the execution of the tasks.

At the end of each task, we asked participants to rate its easiness and to give their opinions about the responsiveness of the configuration, how natural the interaction felt while performing the tasks, and whether they experienced problems during the execution of each task (e.g., dizziness, nausea, tiredness, limited movement). The first three questions were a rating on a five-point Likert scale with appropriate strings as verbal anchors, and the fourth question comprised up to nine different choices (Testing Phase Section).

Participants were monitored during the experimentation, and they could also call for assistance if they did not understand any of the instructions posed. The testing was performed in an isolated environment within our research laboratory to avoid distractions due to the presence of other people. Participants were also encouraged to provide informal feedback (e.g., general comments, suggestions). At the end of the testing, we asked participants to spend a further 15 minutes answering the TAM questionnaire (TAM Section in the questionnaire online).

Finally, the third phase asked participants to fill out a summary survey questionnaire, composed of questions with preferences from among at the most five choices and questions with a rating on a 5-point Likert scale with "strongly agree"/"strongly disagree" as verbal anchors (Summary Survey Section in the questionnaire online).

To avoid a learning effect and to control confounding factors such as fatigue and frustration, a between-group design was employed, with each participant exposed to one experimental condition (Lazar et al., 2010) (which lasted approximately 50 minutes). The entire study required two weeks to be completed.

Recruitment

Participants were students at several departments of the University of Salerno, Italy. They were recruited through word-of-mouth, advertising, and student mailing lists. Their participation was voluntary and anonymous. Participants were informed that all the information they provided would remain confidential.

Data analysis

Non-parametric tests were applied to study differences between the groups testing the defined configurations. The Shapiro–Wilk goodness-of-fit test was used to assess the normality of the data (Shapiro & Wilk, 1965). We recall the reader that the p-value is used in the context of null hypothesis testing in order to quantify the statistical significance, and that the smaller the p-value, the larger that significance. By using regression analysis, we analyzed the influence of the independent variables usefulness, ease of use, attitude toward use, and playfulness (PU, EOU, ATT, PP) on the dependent variable behavioral intention (BI). The internal consistency reliability among the multi-item scales was examined with Cronbach's alpha (Cronbach, 1951). Finally, questionnaire responses were analyzed using SPSS version 20.[3]

6. Results

In this section, we discuss the results of each of the three phases of our evaluation study.

6.1. Preliminary survey results

As shown in Table 2, we recruited 60 participants from among bachelor's (38%) and master's (62%) degree students of the Computer Science, Electrical Engineering, Chemistry, Mathematics, Pharmacy and Medicine, Economics, and Humanities departments at the University of Salerno, Italy. The largest proportion of participants came from the Computer Science field (82%), while only 5% came from the Humanities field. The majority was male (82%) with an average age of 24 years. More than half of respondents (57%) said that they spend less than 7 hours per week playing video games, and more than half (55%) considered themselves to be "competent" in ICT.

Results of the preliminary survey show that participants were very familiar with video games (43% rated themselves as "expert" in the field), but they mostly used traditional input devices, namely mouse and keyboard, to play them (68%). Moreover, when interviewed about their familiarity with natural user interfaces, only 5% gave Leap Motion as an answer.

When interviewed about their familiarity with graph theory, 87% of the participants expressed high familiarity, while "information overloading" was the most rated issue when interacting with a graph (57%). Finally, 22% of the participants stated that they were familiar with VR, while 96% rated themselves as inexperienced with the use of Oculus Rift.

Three questions from the preliminary survey questionnaire (i.e., Q1, Q2, and Q3 in the Preliminary Survey Section) were supplied as input to the k-means clustering algorithm (Berry,

[3]http://www-01.ibm.com/software/analytics/spss/.

Table 2. Participant demographics.

	Number	Percentage
Total participants	60	
Gender		
Male	49	82%
Female	11	18%
Age		
20–23 years	52	87%
24–26 years	6	10%
26+ years	2	3%
Education level attained		
Bachelor's	23	38%
Master's	37	62%
Time playing video games per week		
0–7 hours	34	57%
8–14 hours	18	30%
14+ hours	8	13%

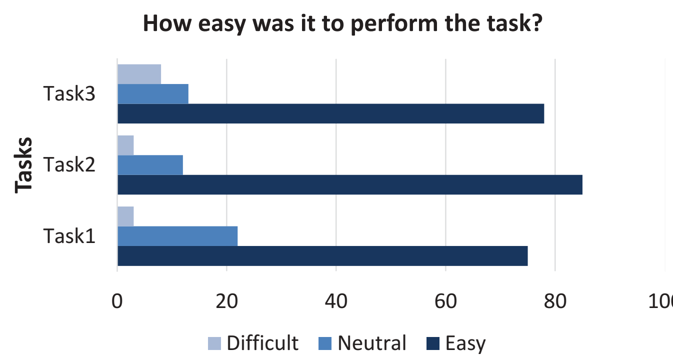


Figure 7. Comparison of tested configurations in terms of easiness of performing tasks.

1997). As a result, we identified three groups of participants: (i) a *NoGamers* group, who do not like video games (15%), (ii) a *LowGamers* group, who do like video games and spend a small proportion of their time playing them (55%), and (iii) a *HardGamers* group, who spend a considerable proportion of their time playing video games (30%).

In summary, the first phase allowed us to build a profile of our participants. Specifically, we identified a subsample of participants interested in video-gaming (who prevalently play strategy/tactical games, 52%, and first-person shooter games, 50%) with high technical skills and high familiarity with graph theory (given the high percentage of Computer Science students). Most of the participants were accustomed to using traditional devices to play video games, whereas both familiarity and experience with Oculus Rift were very low. Although the sample was mostly male, we found that only 2 out of 11 female participants were not gamers (1 *HardGamer*, 8 *LowGamers*).

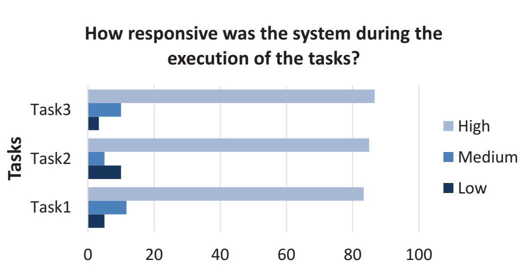
6.2. Testing phase results

The second phase involved interaction with the developed system. Recall that participants were asked to perform three tasks and to evaluate afterwards their easiness (Figure 7), the responsiveness of the overall configuration (Figure 8(a)), and how natural the interactions felt during testing of the configuration (Figure 8(b)).

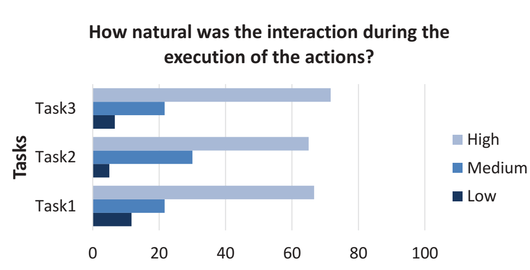
This phase of the study showed that participants rated positively all the posed questions. On average, about 80% of participants found it easy to perform all tasks (see Figure 7). On average, only 6% and 8% of participants expressed difficulties with responsiveness and with the naturalness of interactions with the tested configurations (see Figure 8).

We also analyzed whether differences existed between the six groups (configurations) and whether these were statistically significant. We found that groups did not differ with regard to the questions about the easiness of tasks, the responsiveness of the tested configuration, and the naturalness of movements when interacting with the data. When analyzing the gender factor, we found a statistical difference only for the easiness of tasks (specifically for Task 2 and Task 3, with $p < 0.005$ and $p < 0.01$, respectively). Women experienced more difficulties, with the exception of Task 1, which was found to be the simplest task. We also did not find any statistical difference among the three video-gaming groups (*NoGamers*, *LowGamers*, and *HardGamers*) with regard to these three metrics. Therefore, as a result, the overall system was perceived to be very easy to use and interact with, regardless of the specific tested configuration and regardless of participants' video-gaming skills.

We also asked a question about contradictions that were experienced during the execution of the tasks (questions T1_d, T2_d, and T3_d in the online questionnaire). As indicated in Figure 9, none were experienced by participants testing the *TRConf* configuration. When testing configurations involving the use of Oculus Rift and Leap Motion (*ImmGameConf*, *NUIConf*, *VRConf*), participants expressed problems both of high sensitivity and of limited movement during the execution of the tasks. These problems are mainly due to the limited scope of Leap Motion, and to the low experience of the sample with this



(a) Responsiveness



(b) Natural interaction

Figure 8. Comparison of tested configurations in terms of responsiveness and naturalness of interactions.

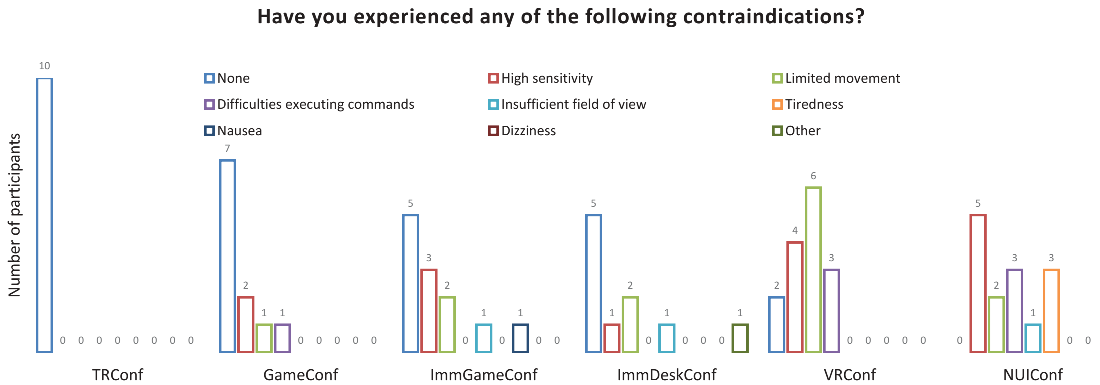


Figure 9. Contradictions experienced during the execution of the tasks, organized according to tested configurations.

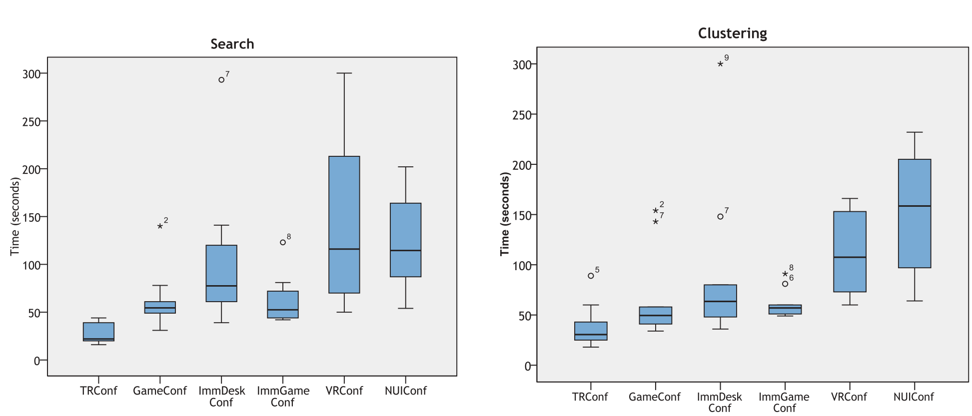
type of interaction (Q13 and Q16 in the online questionnaire). We did not find relevant evidence of a well-known, critical limit of VR headsets (Andreoli et al., 2016), namely cybersickness. One possible explanation for this is that the participants performed the experiments in a sitting position. A more extensive experimental study should be performed to confirm or reject this hypothesis.

During this phase, sessions were monitored to measure the time required by participants to complete the tasks and to measure the corresponding precision/correctness. For Task 1, the correctness is given by the number of nodes that participants were able to find, while for Task 3, the precision is given by the number of clusters that participants were able to build. Participants who tested *TRConf* spent less time completing the tasks (Figure 10). The probable reason for this is that participants had more familiarity with traditional devices than with innovative devices. The most interesting result is that participants were able to complete the tasks efficiently (in terms of finding nodes) with the configurations involving the use of the joypad (i.e., *GameConf* and *ImmGameConf*). Recall that we did not measure the time for Task 2 because for this task we applied a fixed limit of 2 minutes to accomplish it.

Finally, we found statistical differences between the configurations for all the performed tasks ($p < 0.0001$ for Tasks 1 and 3 and $p < 0.01$ for Task 2), highlighting how the observed difference is due to the difference in the controlled independent variables.

In summary, this phase of the study showed that interaction with innovative modalities was more difficult for participants, and led to them spending more time completing the tasks, even with the same precision (see Figures 10 and 11 and Table 3). The worst performance observed, that of the *VRConf* configuration, had several factors, including the inexperience of the student sample with this type of interaction and the distraction element introduced by the novelty represented by Oculus Rift. In fact, many of the participants, although they were encouraged to complete the task as quickly as possible, spent more time because they enjoyed the experience and took time exploring the network. Moreover, when analyzing correlations between completion times and the gaming abilities of participants, we did not find any significant statistical differences. However, we found that *LowGamers* took more time for both tasks. The reasons for this could be, first and foremost, their lack of knowledge of that field and, additionally, the fun experienced during the evaluation phase (more details will be provided next in this section). The configurations involving the use of the joypad as input device showed interesting results in terms of performance and correctness.

At the end of the testing phase, we asked participants to respond to the TAM questionnaire. Reliability values (Cronbach's alpha) in terms of all participants' answers are 0.83 (above the recommended threshold value of 0.70 given in



(a) Time required to complete Task 1

(b) Time required to complete Task 3

Figure 10. Comparison of tested configurations in terms of time taken to complete Tasks 1 and 3.

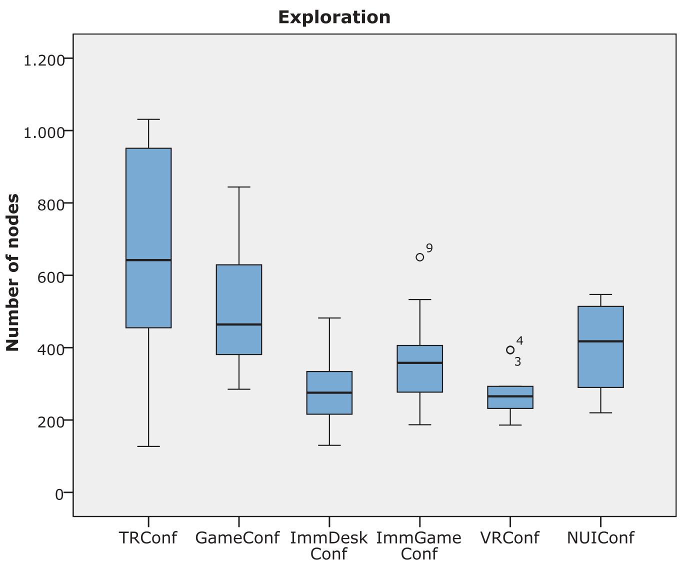


Figure 11. Comparison of tested configurations in terms of time taken to complete Task 2.

Table 3. Results of task completion times and efficacy. Statistically significant difference at 0.0001 level for Tasks 1 and 3 and at 0.001 for Task 2.

	Task 1 (searching)		Task 2 (exploring)	Task 3 (clustering)	
	Time	Precision	Number of nodes	Time	Precision
TRConf	38	3	624	28	4
ImmGameConf	61	3	371	62	4
GameConf	66	3	514	62	4
ImmDeskConf	91	2	280	101	4
VRConf	113	4	276	134	4
NUIConf	150	4	404	120	4

the literature (*Jum C. Nunnally, 1994)). In Table 4 we show that a correlation exists among all the subscales.*

Intuitively, an increase of usefulness and ease of use would increase behavioral intention to use (Spearman's correlations 0.548 with $p < 0.01$ and 0.382 with $p < 0.01$, respectively).

As shown in Table 5, results were highly positive for all metrics. Specifically, ease of use (EOU) was rated more positively by participants testing *TRConf* and *ImmGameConf* ($p < 0.001$), while attitude (ATT) and behavioral intention (BI) by participants testing *ImmGameConf* ($p < 0.005$ and $p < 0.001$, respectively). For participants testing *VRConf*, the questions rated more positively concerned the perceived playfulness (PP) metric, specifically questions PP3 (*Using the system gives fun to me for my task*) and PP4 (*Using the system stimulates my curiosity*). We also found a significant difference with regard to the PP factor ($p < 0.01$).

Table 4. Correlation coefficients between subscales for all configurations. PU, perceived usefulness; EOU, perceived ease of use; ATT, attitude toward use; PP, perceived playfulness; BI, behavioral intention to use. Correlations significant at 0.01 level (**) and at 0.05 level (*).

Subscale	PU	EOU	ATT	PP	BI
PU	1.0				
EOU	0.496**	1.0			
ATT	0.549**	0.397**	1.0		
PP	0.338**	0.255*	0.492**	1.0	
BI	0.548**	0.382**	0.654**	0.429**	1.0

For the TAM metrics, we also verified whether differences existed among participants when considering their gaming abilities. We found a significant difference about the PP factor, showing how *LowGamers* experienced more fun during the execution of their tasks ($p < 0.02$). As part of the informal feedback, we discovered that *LowGamers* decided to participate in the study mainly because it gave them the opportunity to use the Oculus Rift device. As a result, their experience was enjoyable, despite their lack of knowledge about innovative technologies.

To identify which variables influenced the use of a specific configuration, we carried out a regression analysis. The dependent variable was the behavioral intention to use metric (BI). The independent predictor variables were the TAM subscales (i.e., usefulness, ease of use, attitude toward use, and playfulness). The regression analysis in Table 6 shows that a good predictor for behavioral intention to use was attitude toward use. Specifically, we observed that attitude toward use (ATT) influences the behavioral intention to use the system (BI). When ATT increased, BI increased by a factor of 0.674. More precisely, 50% of the BI variation is explained by ATT.

Attitude toward a behavior is defined as an individual's positive or negative evaluation of performing the behavior. It involves an individual's judgment that performing a behavior is good or bad, and a general evaluation that an individual is either inclined or disinclined to perform the behavior (*Ajzen and Fishbein, 1980). Our results show that a positive attitude toward the proposed configurations and interactions could influence their adoption, confirming previous works that found that some attitudes are strongly predictive of corresponding behaviors (Petty & Krosnick, 1995).*

6.3. Summary survey results

In this section, we report the results of the questions posed in the questionnaire submitted in the third phase of our evaluation study (see Table 7). Generally, as shown in the previous section, all participants rated as positive the usefulness and the ease of use of the tested configurations. We did not find any statistical differences among the six groups. Similarly, we did not find any differences with regard to the demographic factor and gaming abilities.

Additionally, when interviewed about the question: "*For which category of users do you think the proposed system could be useful?*", more than half of participants (67%) stated that the proposed configurations could be very useful for all people and not for domain experts only (22%), and 10% of participants stated that such innovative interfaces could be useful for people with disabilities.

7. Conclusion and future works

In this paper, we have explored the effectiveness of different, both traditional and innovative, technologies to visualize and interact with 3D graphs. Specifically, we compared them in order to derive useful insights about their effectiveness, easiness, appeal, and playfulness. In order to compare the

Table 5. TAM measures and constructs.

	VRConf	*TRConf*	*NUIConf*	*GameConf*	*ImmGameConf*	*ImmDeskConf*	Sig. Level
PU	4	5	4	5	5	4	N.S.
EOU	6	7	5	6	7	6	< .001
PP	7	6	6	6	6	7	< .01
ATT	6	5	6	6	7	6	< .005
BI	5	5	5	6	7	6	< .001
Mean	5	5	5	6	6	6	
SD	0.9	0.8	0.6	0.3	0.6	0.9	

Table 6. Results of multiple linear regression analysis. B, unstandardized coefficient; β, standardized coefficient; SE, standard error. Adjusted R^2 = 50%.

Predictor variables	B	SE(B)	β	*t* value	*P* value
(Constant)	0.657	0.936		0.702	0.486
Usefulness	0.138	0.105	0.171	1.318	0.193
Ease of use	0.099	0.136	0.087	0.728	0.470
Playfulness	− 0.021	0.136	− 0.018	− 0.153	0.879
Attitude	0.674	0.157	0.569	4.289	0.000

different configurations, we selected a set of gesture for hand and finger tracking enabling the users to explore and navigate a 3D graph. In the absence of any standard related mid-air interaction, the set of gestures were designed to be similar to those adopted in the interaction with touch-based handsets which leverage familiar interactions.

Our evaluation study showed that participants found the use of innovative technologies to be more challenging, compared with the use of traditional devices, while performing the same tasks. Meanwhile, easiness was rated more positively by users testing *TRConf* (the configuration involving devices common among video gamers); fun, curiosity, exploration, and imagination were felt in a positive way mainly when using Oculus Rift, and in particular by *LowGamers* users. Moreover, the worst performance observed, that of the *VRConf* configuration, had several factors, including the inexperience of the student sample with this type of interaction and the distraction element introduced by the novelty of Oculus Rift. Finally, the configurations involving the use of a joypad as input device (*GameConf* and *ImmGameConf*) showed interesting results in terms of performance and correctness.

We found that by intervening on factors such as positive attitudes we were able to foster their usage. Exploiting the playfulness aroused by VR, the configuration that combines Oculus Rift with a joypad device may reduce users' difficulties with its complexity, given the positive results in its performance and correctness.

This work has some limitations. First, all participants were students from an Italian academic environment. Our samples were composed of users with high education levels and with an age ranging from 20 to 30 years. Moreover, they were mostly gamers, ICT skilled, and very familiar with graph theory. Therefore, our results may not necessarily be representative of the entire world population. We are planning an extensive and representative experimental study involving a larger sample of people, including older age groups, with more diversified technological skills as well as with no knowledge of the whole setting. The aim is to study how non-gamer users, as well as users who are not familiar with the considered domain, would react to the proposed approaches.

Moreover, in the first analysis, for our tests in the evaluation study, we used a graph of Java dependencies. Our aim here was to analyze users' interactions regardless of the navigated graph and derive information about which interaction modality was most effective and usable. Upon identifying this best interaction modality, in further work we can extend the set of graphs to derive insights about which type of graph (e.g., sparse, dense) could benefit 3D exploration. We are going also to investigate also the subjective arm fatigue of our set of gestures using the recent cumulative fatigue model (Jang, Stuerzlinger, Ambike, & Ramani, 2017). In addition, we intend to investigate more advanced input devices, such as Oculus Touch Controller, that enable users to know where their hands are and what their fingers are doing. These controllers provide a more immersive VR experience, but require the creation of new user interface, which is a design goal that will require a clear viewpoint, careful design and testing, and methodological evaluation. Finally, we would like to transfer our results to other contexts. This is a challenging problem because the literature has shown that users have different gesture preferences and that variability exists in gesture articulation. Also, gesture production in public spaces depends on location and audience and the social acceptance of gestures is influenced by culture, time, and interaction type. However, recently the problem of gesture knowledge transfer across multiple contexts of use has been tackled (Vatavu, 2017b). We hope in the future to have a reference model in order to validate our results to non-graph 3D interactions.

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Table 7. Summary survey results. 5-point Likert scale. Mean (standard deviation) results.

Question	VRConf	TRConf	NUIConf	GameConf	ImmGameConf	ImmDeskConf
Did you find it useful to use the proposed system?	4.1 (0.6)	3.9 (1.1)	4.5 (0.5)	3.8 (1.6)	3.7 (1.6)	4.1 (1.3)
Did you find it interesting to use the proposed system?	4.5 (0.5)	3.3 (1.2)	4.3 (1.3)	3.8 (1.6)	3.8 (1.5)	4.4 (1.3)
Did you find it easy to use the proposed system?	3.5 (1.4)	3.7 (1.3)	4.1 (1.0)	3.9 (1.4)	4.0 (1.6)	4.5 (1.3)

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